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SURFACE EFFECTS SKIMMER DEVELOPMENTS

Nicholas P. Trentacoste

Science Applications, Incorporated

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SURFACE EFFECTS SKIMMER DEVELOPMENT

By

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16. ABSTRACT

This experimental program investigated the use of a Surface Effects Skimmer in removing thin film oil slicks spread over large water areas by fast currents. This new skimmer uses a directed air jet to separate and lift spilled oil from the surface of the water in the form of a spray consisting of oil and water droplets. The oil/water spray is directed toward a rotating belt of polyurethane foam from which it is squeezed and pumped to a nearby storage tank. Initial experiments were performed in a 20 cm wide flume. Subsequent tow tank tests were conducted at speeds up to 3.25 knots in calm, choppy and smooth wave conditions with oils ranging from a very viscous Venezuelan crude to a very light No. 4 distillate fuel oil. During tests at a tow speed of 3.25Kts in the presence of 13.75 cm high waves oil collection efficiencies of more than 80% were achieved with the Venezuelan crude oil and of about 60% with the No. 4 distillate fuel oil. In a related series of experiments, it was found that presoaking the polyurethane foam belt in either water or oil had no effect on its ability to retain oil.

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment - air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

This report represents an effort to develop new technology for removing spilled oil from surface waters. This advanced technology will be useful in protecting the environment from the adverse effects resulting from an oil spill into water.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

The development of equipment to remove thin film oil slicks which have been spread over large areas by fast currents has eluded significant technical progress. The purpose of the current experimental program was to determine the utility of the Surface Effects Skimmer (SES) in performing this function. The principle of operation of this new skimmer is that of using a directed air jet to separate and lift the oil slick from the surface of the water in the form of a spray consisting of oil and water droplets. Moreover, the oil/water spray is directed toward a rotating belt of polyurethane foam from which it is squeezed and pumped to a nearby storage tank. Initial experiments performed in a 20 cm wide flume proved that this oil removal concept was viable. Subsequent tests were conducted with a 61 cm wide skimmer model in a 30.5 m long, 3.65 m wide and 0.75 m deep tow tank. Tests were conducted at speeds up to 3.25 knots in calm, choppy and smooth wave conditions with oils ranging from a very viscous Venezuelan crude to a very light No. 4 distillate fuel oil. The results of these tests at a tow speed of 3.25 knots in the presence of 13.75 cm high waves were encouraging since oil collection efficiencies in excess of 80% were achieved with the Venezuelan crude oil whereas efficiencies of about 60% were obtained with the No. 4 distillate fuel oil. In a related series of experiments, it was found that presoaking the polyurethane foam belt in either water or oil had no effect on its ability to retain oil.

This report was submitted in fulfillment of Contract Number 68-03-0327, by Science Applications, Inc., Energy and Environmental Services Company under the sponsorship of the Environmental Protection Agency. Work was completed as of September 1974.

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The suggestions offered by Mr. Frank Freestone of EPA were very useful; in particular the application of the rotating belt of polyurethane foam proved to be the most effective means of collecting and separating the oil from the water.

A sincere thank you must also go the entire EPA Oil Spills Branch staff for providing their tow tank test facility during the program.

SECTION I

CONCLUSIONS

The test results indicate that the Surface Effects Skimmer is a viable means of cleaning up thin (~0.1 mm) oil slicks in fast currents (~3.25 knots).

Oil collection efficiencies in excess of 60 and 80% were achieved with the very light No. 4 distillate fuel oil and the viscous Venezuelan crude oil respectively. Test results have shown that an 83% oil collection efficiency was achieved under the following conditions: 0.1 mm Venezuelan crude oil slick thickness, 3.25 knot current, and 13.75 cm high and 4.5 to 6.0 m long waves. Moreover a 62% oil collection efficiency was obtained under the following conditions: 0.1 mm No. 4 distillate fuel oil slick thickness, 3.25 knot current, and 13.75 cm high and 4.5 to 6.0 m long waves.

Operation of the Surface Effects Skimmer from calm through wavy water conditions showed an increase in oil collection efficiency of 30%. Choppy water tests were also conducted and showed a 15% increase in oil collection efficiency over the calm water tests.

The highest oil collection efficiencies were achieved with the 60 pores per inch (ppi) polyurethane foam for the No. 4 distillate fuel oil and with the 20 ppi foam for the viscous Venezuelan crude oil. However, in a related series of experiments, it was found that presoaking the polyurethane foam belt in either oil or water had no significant effect on its ability to retain oil.

The use of a small hydrofoil placed below and parallel to the air jet nozzle prevented the formation of a strong water vortex in the vicinity of the nozzle and directed the oil/water flow to the region of influence of the air jet. This latter situation resulted in a 10% increase in oil collection efficiency over the case where the hydrofoil was not present.

An optimum air jet nozzle submergence depth exists for the Surface Effects Skimmer. This optimum depth was not precisely identified during the experimental program, but it appears to be in the neighborhood of 1.5 cm below the water surface.

A velocity exists below which the skimmer will not operate. If the skimmer velocity is too low, then the air jet merely pushes the surface oil layer along in front. Thus, a skimmer velocity in excess of that which maintains an equilibrium between the oil/water friction and gravity forces must be exceeded before the skimmer can function. Through experimentation, this minimum velocity has been found to be in the neighborhood of 1.0 knot.

SECTION II

RECOMMENDATIONS

An optimum Surface Effects Skimmer design can only be achieved through a better understanding of the interaction of the air jet with the oil/water surface layer.

Further testing of the 61 cm wide skimmer model in the 30.5 m long tow tank is recommended so that the optimum placement of the hydrofoil with respect to the nozzle and the proper nozzle submergence depth and exit velocity can be identified. These latter parameters have a very significant effect on the performance characteristics of the Surface Effects Skimmer.

It is also recommended that a 122 cm wide skimmer model be constructed and tested at OHMSETT. The purpose of the 122 cm wide model is to minimize the effects of vortices emanating from the skimmer sidewalls and to reduce the deleterious impact of the sidewalls on the oil collection efficiency.

The reasons for choosing OHMSETT for testing the 122 cm wide model are: (1) longer run times can be achieved, thereby increasing the credibility of the oil collection efficiency calculations; and (2) faster towing velocities (~6.0 knots) and larger (~60 cm) and more complex wave structures can be obtained.

SECTION III

INTRODUCTION

A number of techniques have been developed or are under development to facilitate in the cleanup of massive oil spills and spills which have spread to a thin film covering a large area of water. These techniques may be thought of as belonging to one of the following three categories: (a) chemical; (b) containment; and (c) removal. The chemical and containment techniques do not solve the entire problem of removing oil from the water, but may aid the third category by lending support to the oil removal process. The latter category of techniques is important since the physical removal of oil from the water surface is clearly the most desirable from the ecological point of view.

One of the basic requirements of an efficient oil removing device is its ability to gather large volumes of oil within a short period of time. The incorporation of this design feature will aid in reducing the operating costs as well as preventing the spill from increasing in size and possibly reaching a nearby shoreline. The equipment must also be mobile and maneuverable, thus having the ability to cover large areas quickly while avoiding floating debris as well as not interfering with shipping or shore operations.

Operation in high winds (~35 knots), in strong currents (~5 knots), and high seas (~150 cm) are also basic requirements for effective oil-slick removal equipment. The minimization of unfavorable environmental consequences resulting from the operational characteristics of the device is another prime factor in its consideration for widespread use. This equipment also should be simple to operate and require a minimum of logistical support. Consideration must also be given to optimizing the size and cost of the device for different oil spill requirements.

Considerable advances have been made in developing oil spill removal equipment that meet the above criteria. However, one area in particular has eluded significant technical progress; that is, the removal of thin oil slicks that have been spread over large areas by fast water currents. The purpose of the present research program was to investigate a device that would be applicable to this oil spill situation.

The program was divided into two phases. The first consisted of small scale flume experiments which were conducted to determine the feasibility of the proposed skimmer concept and to identify potential problem areas. During the second phase of the program a prototype skimmer model was designed (from the information developed during the small scale flume experiments), constructed and tested in a tow tank. The purpose of these tests was to investigate a broad range of conditions under which a full scale system would have to operate, and to identify operating limits of the device. The primary factor that determines these limits is the oil collection efficiency achieved under a given set of circumstances.

SECTION IV

SURFACE EFFECTS SKIMMER DESIGN AND OPERATIONAL CHARACTERISTICS

This new skimmer device uses a directed air jet to separate and lift the oil slick from the surface of the water in the form of a spray consisting of the oil and a portion of the water surface. One possible application of this technique involves the utilization of the excess cushion flow from a surface effects vehicle (SEV) or air cushion vehicle (ACV) as an air jet source to separate the oil slick from the surface of the water. During normal SEV or ACV operations, the excess cushion air flow escapes from under the vehicle and interacts with the water surface and develops a water spray that surrounds the vehicle. Normally, this escaping water spray is not recovered and therefore represents an inefficiency of the SEV or ACV. Thus, the new skimmer could utilize the air jet principle either directly (by using an ACV or SEV) or indirectly, by installing a similarly constructed air jet unit on a vessel of opportunity. For the present program, the latter avenue of development was chosen, primarily because of the excessive cost involved with SEV or ACV type of craft and the flexibility in design and application allowed by a device that can be employed on any waterborne craft.

Once the oil/water mixture is in the air, a collector is utilized to intercept the spray before it impacts the water surface (see Figure 1). In the current design, the collector is a rotating belt of polyurethane foam. This material has the property of being oleophilic and hydrophobic; therefore, the oil will remain in the belt whereas most of the water will be repelled. Once the mixture has been adsorbed/absorbed into the belt, it can be squeezed out, collected in a sump and pumped from there to a storage tank. The advantage of using a polyurethane foam belt as the collection medium is that the oil/water separation, for the most part, is performed at the belt. Effecting the greater portion of oil/water separation prior to storage on the skimming vessel permits a tremendous reduction in the required storage volume and a

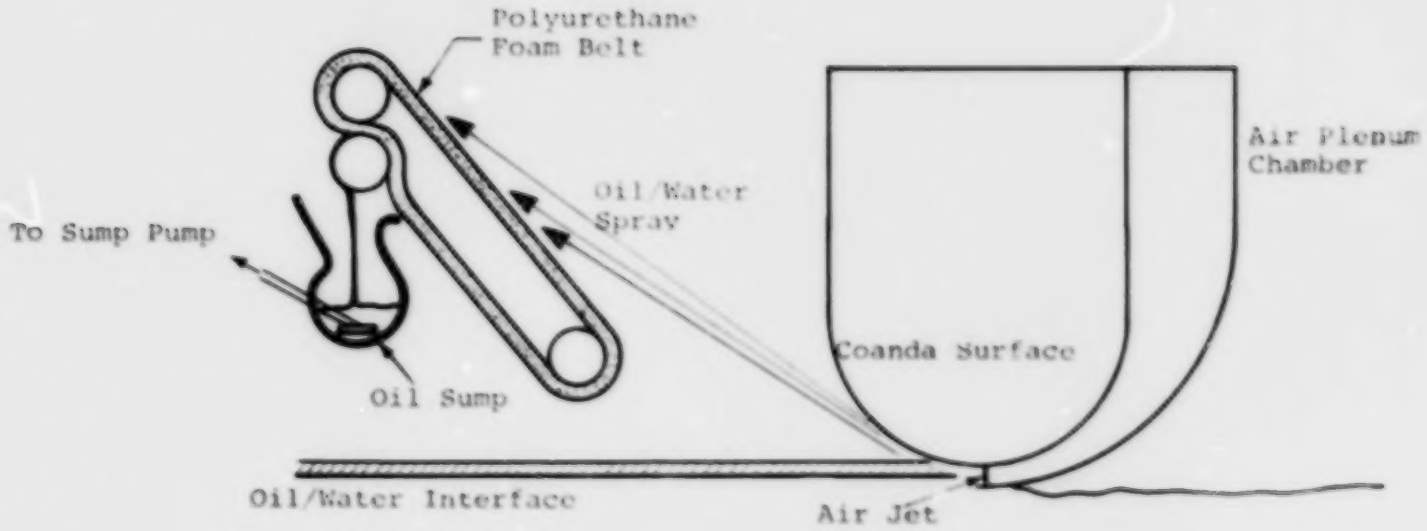


Figure 1. Schematic representation of surface effects skimmer operating characteristics

corresponding increase in operating time between emptying of storage tanks. Moreover, if further oil/water separation is required, it can be performed at a location remote from the actual skimming operation.

The previous remarks coincide directly with all three prime objectives necessary for the achievement of a significant advance in the state-of-the-art of oil spill clean-up devices, i.e., a high degree of mobility, operation in rough waters, and a large volumetric capacity. In addition, this device will have a minimum of environmental impact because it does not require the use of any chemical additives to contain or coagulate the oil slick. The principle of operation of the device is simple, and the entire system of the air jet and collector will interface well with existing environmental technology. A minimum of logistical support is required for the successful operation of this system; in fact, the device, if integrated into an ACV or SEV, can become a part of a larger operation (sea-search, rescue and oil spill removal). Here, the device can be transported under its own power at 30 to 40 knots to the site of a spill, whereas most other devices must either be air-lifted or carried aboard another ship to the site. On the other hand, if developed (as in the current context) as a separate device and manufactured in modular units, it can be employed in a variety of oil spill clean-up operations with great flexibility.

Thus the Surface Effects Skimmer is extremely versatile and provides a unique way in which to remove thin film oil slicks.

SECTION V

DESCRIPTION OF EXPERIMENTAL PROGRAM

The experimental program can be logically divided into two phases. The first is oriented towards developing design criteria for a prototype skimmer model. The second phase is concerned with the design, construction and testing of a full scale section of the prototype skimmer.

Prior to discussing the details of the current program, a brief description of the previous in-house effort is appropriate.

INITIAL OIL SKIMMER TEST PROGRAM

In order to test the principle of operation of the Surface Effects Skimmer, a 15 cm diameter wood model of the SES was constructed. The air supply used for this demonstration was obtained from a vacuum cleaner which was connected via a flexible plastic hair-dryer hose as shown in Figure 2. The model was then placed inside a 45 cm diameter basin filled with water to about 5 cm below its top ledge. Two types of oil were used in the demonstration, SAE 30 and 90. A film of oil approximately 0.1 mm in thickness was deposited on the surface of the water. When the air supply was turned on, very little spray was developed; the main effect of the escaping air flow was to push the oil slick toward the walls of the basin. Moreover, no noticeable effect of using the two different oils was observed.

At this point, it was decided to redesign the SES model to incorporate a different mode of operation (the peripheral jet), so that a high velocity jet would be generated. Thus, an insert was added to the underside of the SES model so that the air flow would be directed as if it were flowing through a nozzle. The latter modification to the SES model is shown in Figure 3. When the air supply was turned on, with the SAE 90 oil film on the water surface, a large spray of oil and water resulted. A portion of the oil/water spray escaped from the basin, but most did not. The spray that did not escape struck the sides of the basin and subsequently rolled down and was found to concentrate itself along the inside perimeter of the basin at the water surface. When the SAE 30 oil was used in the test, it behaved similarly except that an emulsion of the

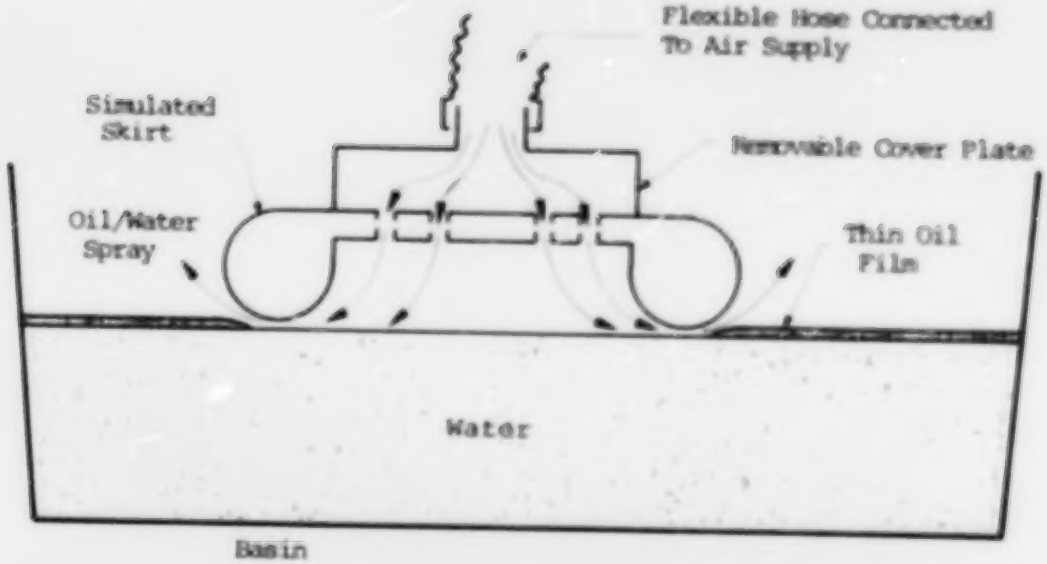


Figure 2. Large volume/low pressure surface effects skimmer demonstration model

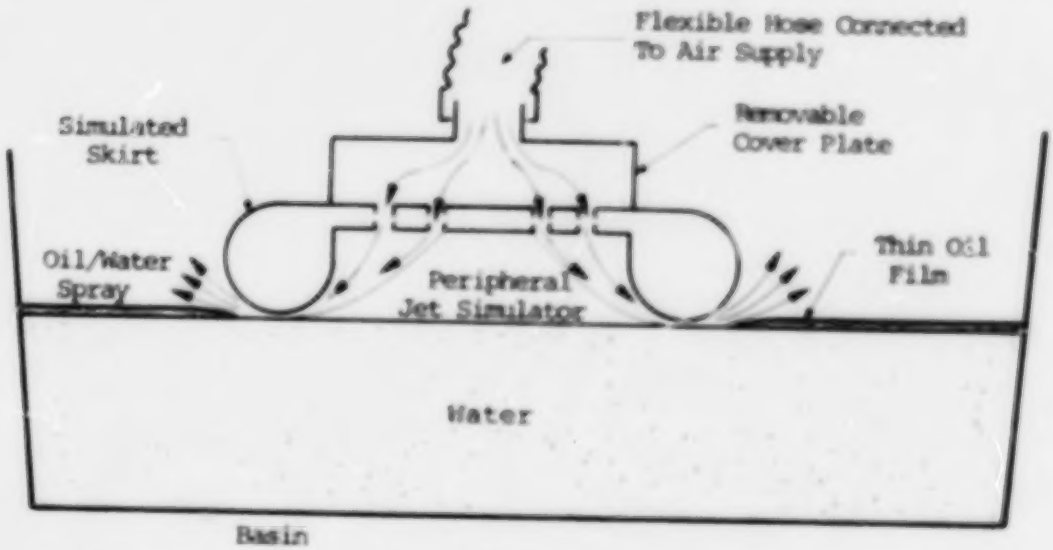


Figure 3. Small volume/high pressure peripheral jet surface effects skimmer model

oil and water formed. It is believed that the formation of the emulsion is a result of the fact that the SAE 30 oil used for these tests was a detergent oil which is susceptible to emulsification, especially when agitated in the manner described above (and is not a direct result of the oil skimming technique).

The conclusion reached from this demonstration was that the new skimmer device, using the peripheral jet model of operation, performed well and that further testing in a larger facility was warranted.

TWO-DIMENSIONAL FLUME TESTS

A series of tests were conducted in a two-dimensional recirculating water flume in order to demonstrate the SES concept and to obtain design data for a larger scale model. These tests were also used to identify possible limiting conditions for operation of the skimmer and to obtain information on potential problem areas.

The facility used for these tests is shown schematically in Figure 4 and is constructed primarily of plywood and plexiglass. The sidewalls of the flume are plexiglass to permit easy viewing of the SES simulator model in operation. The overall dimensions of the facility are 2.45 m in length, 0.92 m in height and 0.25 m in internal width. Water is continuously recirculated in the channel at velocities up to 1.0 knot and at depths not exceeding 15.0 cm. The depth of water in the channel was controlled by a weir located at the far end of the tank. The direction of water flow was opposite to that of the air jet for all of the tests conducted. Oil was introduced upstream of the test device and carried to the SES simulator by the water current. When the oil reached the region of influence of the air jet, it was lofted into the air and onto a sheet of polyurethane foam which was used as the collection medium. The air jet nozzle exit configuration, its depth of submergence and its exit velocity were all variables in the test series described below.

Test Series 1

The purpose of these tests was to qualitatively determine the behavior of the SES in a larger scale than had been previously tested. Moreover, the results of these tests would determine future modifications to the device as well as the type of experiments to be conducted. Experiments were performed with the peripheral jet simulator shown in Figure 5. The nozzle exit plane was a 20.0 cm wide, 0.63 cm high slot, and the air supply consisted of a 0.5 horsepower vacuum cleaner. The maximum air jet velocity was 53 m/sec. The experiments revealed the following:

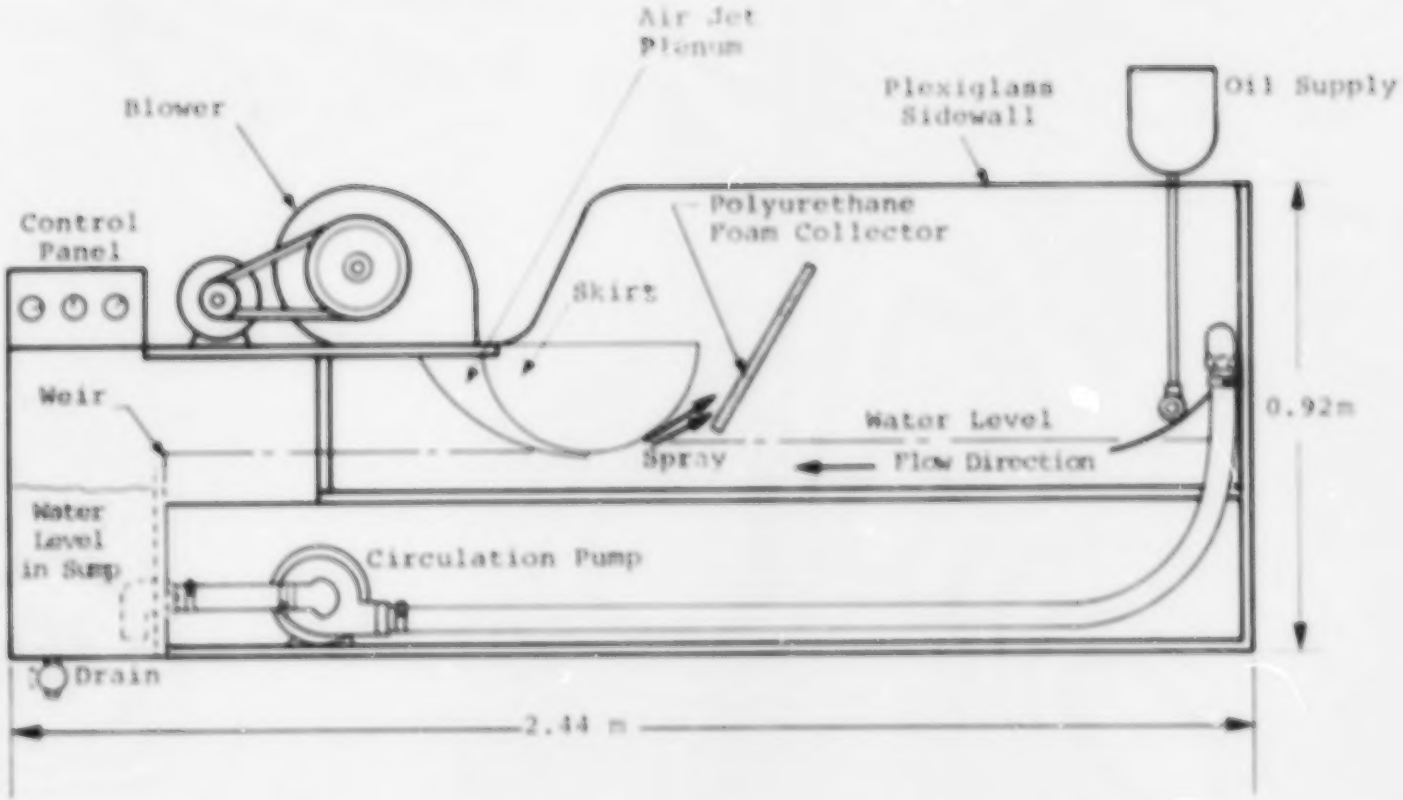


Figure 4. Schematic drawing of two-dimensional water flume test facility

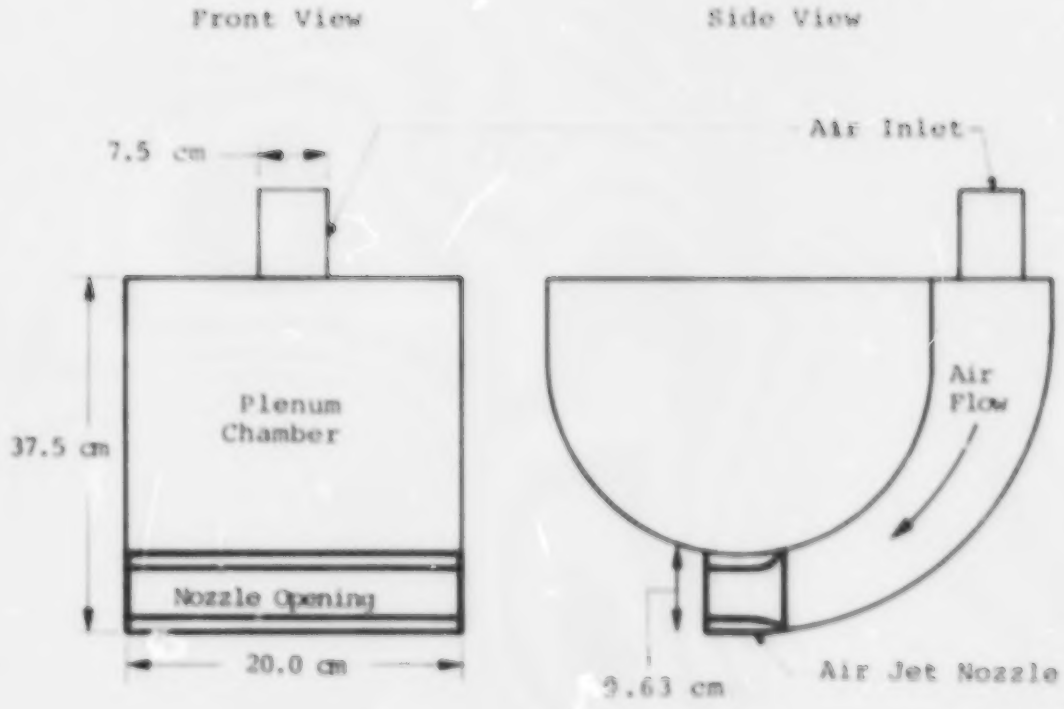


Figure 5. Two-dimensional peripheral jet simulator model

The quantity of spray raised from the water surface is directly proportional to the power (power $\propto V^2_{JET}$) in the skimmer air jet.

The water spray characteristics change significantly with air jet velocity. The following effects were observed:

At low jet exit velocities (<45 m/sec), a heavy, short range spray was raised which consisted of large droplets and splashes. In addition, a strong water vortex was generated with its axis parallel to and below the air jet exit plane (see Figure 6).

At higher jet exit velocities (>45 m/sec) a much finer, longer range spray resulted. In addition, much less tendency to form a horizontal vortex under the skimmer was noted.

The presence of a vortex under the skimmer increases the chance that oil may escape past the skimmer, since oil droplets can occasionally become entrained in the horizontal vortex and thus be driven well below the water surface. This was the only mechanism observed by which oil passed the skimmer.

In all cases, a very thin oil film on the surface was initially driven away from the skimmer by the air jet (oil in the immediate vicinity of the jet is lifted off with the spray). A differential head of surface oil is built up, counterbalancing the small shear forces in the far field of the skimmer jet which again brings the surface oil within range of the jet pickup spray. The amount of differential head of the surface oil necessary to restore pickup action is dependent on the far field wind velocity at the surface and the flow speed. Higher speeds will reduce the lag time of this "pile up."

Test Series 2

The purpose of this test series was to explore the effects of various air jet exit configurations, their depth of submergence in the water and the overall exit velocity on the characteristics of the water spray. These tests were conducted without oil on the surface of the water, and with and without water flowing in the two-dimensional flume. In order to obtain higher air jet velocities, a second vacuum cleaner of 0.5 horsepower was added to the air supply system. This second vacuum raised the air jet plenum chamber pressure from 35 mm to 50 mm of mercury (Hg). The rise in the plenum pressure increased the maximum air jet velocity from 53 to 92 m/sec.

A photograph of the two-dimensional water flume appears in Figure 7 and a close-up view of the test section area is shown in Figure 8. Also shown in Figure 8 is the manometer used to record the air jet plenum chamber and nozzle exit pressures. A pitot tube can also be seen installed on a traversing mechanism.

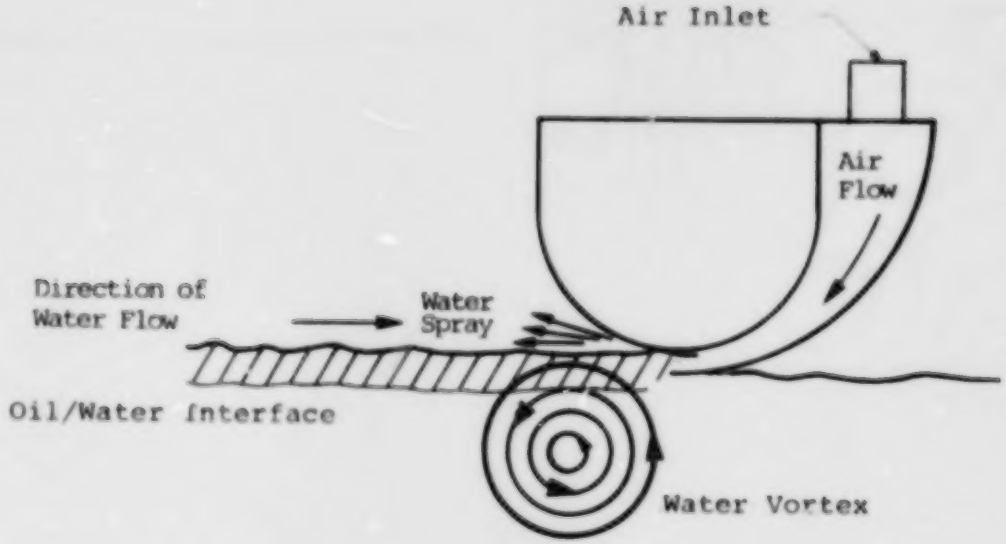


Figure 6. Water vortex formed at low jet exit velocities

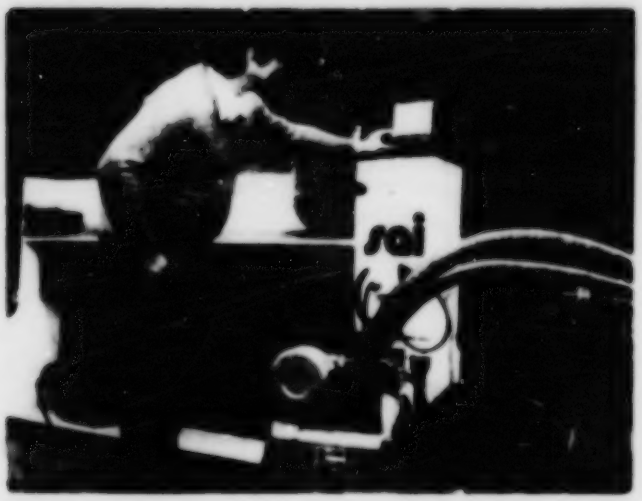


Figure 7. Photograph of two-dimensional water flume test facility

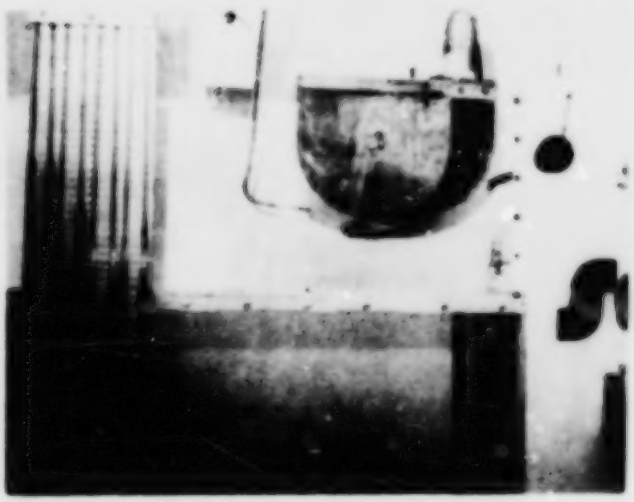


Figure 8. Photograph of peripheral jet simulator model installed in two-dimensional water flume

Three 20.0 cm long plexiglass nozzle inserts (Figures 9a, b, c) were constructed for these tests. The first nozzle (Figure 9a) is a simple rectangular slot whose height is variable between 0 and 3.0 mm. The second nozzle (Figure 9b) consists of two alternating rows of 0.16 cm diameter holes, whereas the third nozzle configuration (Figure 9c) is composed of a series of alternating rectangular slots. The purpose of using the various nozzle exit configurations was to determine if any particular one would be effective in eliminating the formation of water ligaments and in reducing the average water droplet dimension in the spray. It is believed that the smaller diameter droplets are better absorbed/adsorbed by the polyurethane foam because of their ability to penetrate the fine mesh foam material. Moreover, although there is no definite proof, if one were to aerodynamically produce small diameter droplets from larger ones, it is believed that the difference in surface tension between the oil and water would result in the formation of independent oil and water droplets. These latter droplets would result from single oil/water droplets and would aid the oil/water separation function of the polyurethane foam.

A series of air flow and water spray tests were conducted to determine the characteristics of the flow resulting from the three nozzle configurations shown in Figures 9a, b, and c. The results of these tests are described below:

Air Flow Tests -

The first series of tests performed with the three nozzle designs consisted of a determination of the total pressure distribution in the vicinity of the jet exit. The total pressure at the jet exit and in the transverse direction was obtained for each of two slot heights (1.5 and 3.0 mm) for the rectangular slot nozzle. The pressure distribution was found to be extremely uniform across the slot, thus indicating that the flow upstream of the nozzle exit, in the plenum chamber, was properly diffused. Less uniformity in the exit total pressure was found for the alternating rectangular slot nozzle. Upon further investigation, it was found that the geometry of the alternating slots varied considerably from one slot to another. A similar shortcoming was observed in the nozzle consisting of a series of alternating circular holes. In order to overcome these nozzle construction deficiencies, a new set of nozzle inserts were manufactured using more accurate machining facilities.

Water Spray Tests -

At this point, it was decided not to obtain quantitative data on the generation of spray from the aforementioned nozzles. However, a series of experiments was performed to determine the qualitative aspects of the spray formation. Each of the

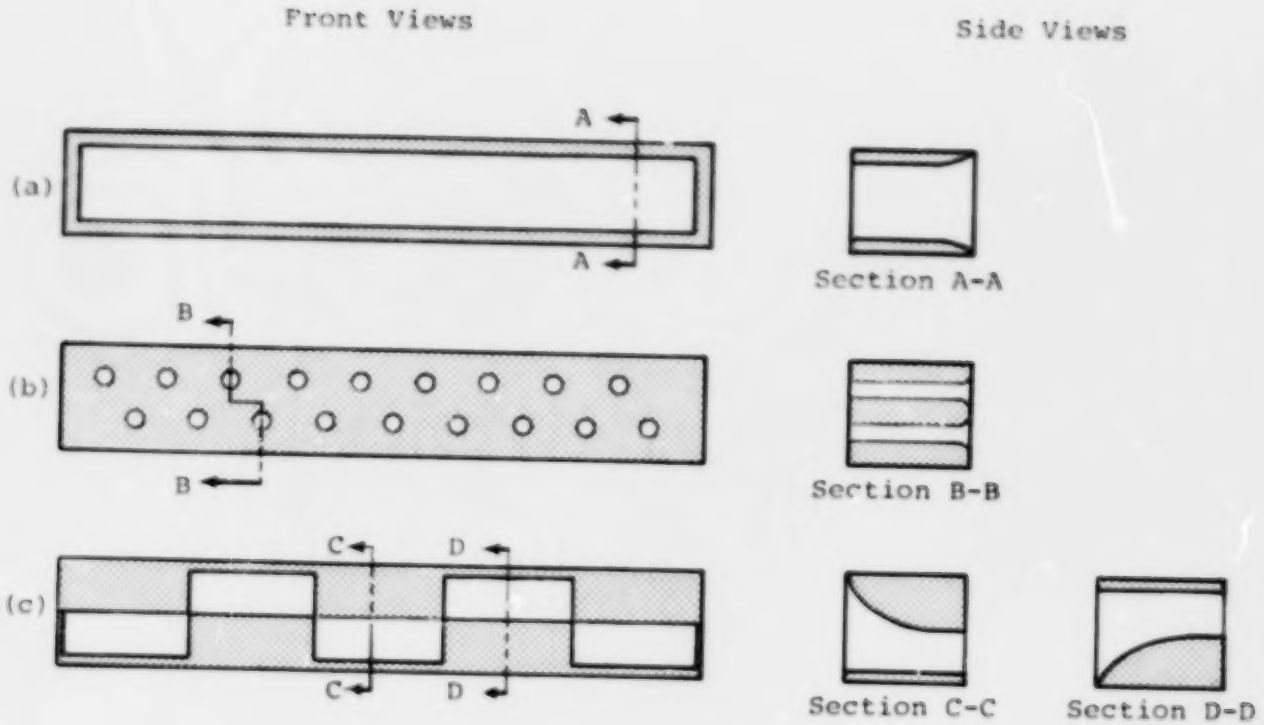


Figure 9. Front and side views of air jet nozzle inserts: (a) rectangular slot; (b) alternating circular holes; and (c) alternating rectangular slots

three nozzle types described earlier were tested at varying depths of submergence in water (measured from the nozzle's lower lip) to determine in a qualitative way the droplet sizes, spray trajectory, and the spanwise uniformity of the spray. These tests were conducted with and without a water flow in the two-dimensional flume.

Rectangular slot nozzle (3.0 mm high slot) - A low jet exit velocity was obtained with this nozzle because of its relatively large exit area. This condition resulted in "chugging" (pulsations in the water near the nozzle lip as well as water escaping upstream and below the nozzle exit). Two tests were performed at different nozzle submergence depths, h, of 0 and 20 mm with a 1.0 knot water flow in the flume. Some spray was produced in both tests, but the droplet size appeared to be rather large and in some regions continuous ligaments of water were formed. The droplet size as well as the quantity of spray increased with increasing depth of submergence of the nozzle.

Rectangular slot nozzle (1.0 mm high slot) - In order to obtain a higher exit velocity with the rectangular slot nozzle, its height, and thus, its area were reduced. The use of a higher velocity jet eliminated the "chugging" problem observed in the previous tests. Several nozzle submergence depths were tested. For the case of h = 0 mm, two tests were performed, one with and the other without water flowing in the tank. In either case, the spray was still rather coarse but more spray was produced with water flowing. As the depth of submergence was increased from h = 0 to h = 35 mm, a higher water spray trajectory was observed as well as increased water droplet diameters.

Series of alternating circular holes - three depths of submergence were tested with this nozzle configuration, h = 0, 15 and 35 mm. The same general spray characteristics were noted as with the rectangular slot nozzle with the exception that the spray was composed of slightly smaller droplet diameters.

Alternating rectangular slot nozzle - As in the previous case, three depths of nozzle submergence, h = 0, 15 and 35 mm were investigated. However, for the case of h = 15 mm, two individual tests were performed, one with and the other without water flowing in the test facility. For the case of h = 0 (with water flow), a finer spray was produced than in either of the two preceding nozzle designs. However, some spanwise non-uniformity in the spray was observed. This non-uniformity was the result of similar non-uniformities in the construction of the individual rectangular slots. For the case of h = 15.0 mm, but with no flow in the tank - the formation of much smaller water droplets was observed. The same general characteristics of increasing droplet diameter and quantity of spray with increasing depth of submergence were noted for this nozzle configuration as in the others. However, a much finer spray is produced with the alternating rectangular nozzle configuration.

High velocity tests - A second vacuum cleaner was added to the pressure supply system (with the alternating rectangular slot nozzle installed) thus raising the plenum pressure from 35 to 50 mm of mercury (Hg). A much finer spray was produced with the higher pressure, thus indicating that higher jet velocities will generate better water sprays. A rough estimate of the water droplet size indicated that the greater majority of droplets were in the 1.0 mm diameter range.

Thus it can generally be concluded from these tests that:

(1) The alternating rectangular slot nozzle (Figure 9c) produces a spray containing the largest number of small diameter droplets.

(2) Higher jet exit velocities result in smaller diameter droplets as well as longer trajectories.

(3) A larger quantity of spray is produced by increasing the depth of nozzle submergence (h); however, the droplet diameter also increases.

(4) Continuous ligaments of water were produced by the rectangular slot and alternating series of holes nozzles, but not with the alternating rectangular slot nozzle.

(5) Improved nozzle construction will result in more uniform spanwise distribution of the spray.

Test Series 3

The purpose of test series 3 was to select the most favorable nozzle design to be used on the first prototype skimmer model from among the four new designs developed after a careful review of the previous test results. In addition, the results of test series 2 indicated that a larger volume/high pressure air blower would be required for further testing in the two-dimensional flume.

Description of High Pressure/Large Volume Blower -

In order to achieve air jet velocities in the range of 150 m/sec, a high pressure (7 psig) and large volume (800 CFM) air blower is required. A Paxton CB-80-H blower with a 25 horsepower Onan gasoline engine met these requirements and was purchased. The operating characteristics of the blower are shown in Figure 10 and the results of its calibration appear in Figure 11.

Description of Nozzle Designs -

Detailed schematic drawings of the four (4) new nozzle exit designs are shown in Figures 12 through 15. The reasons for

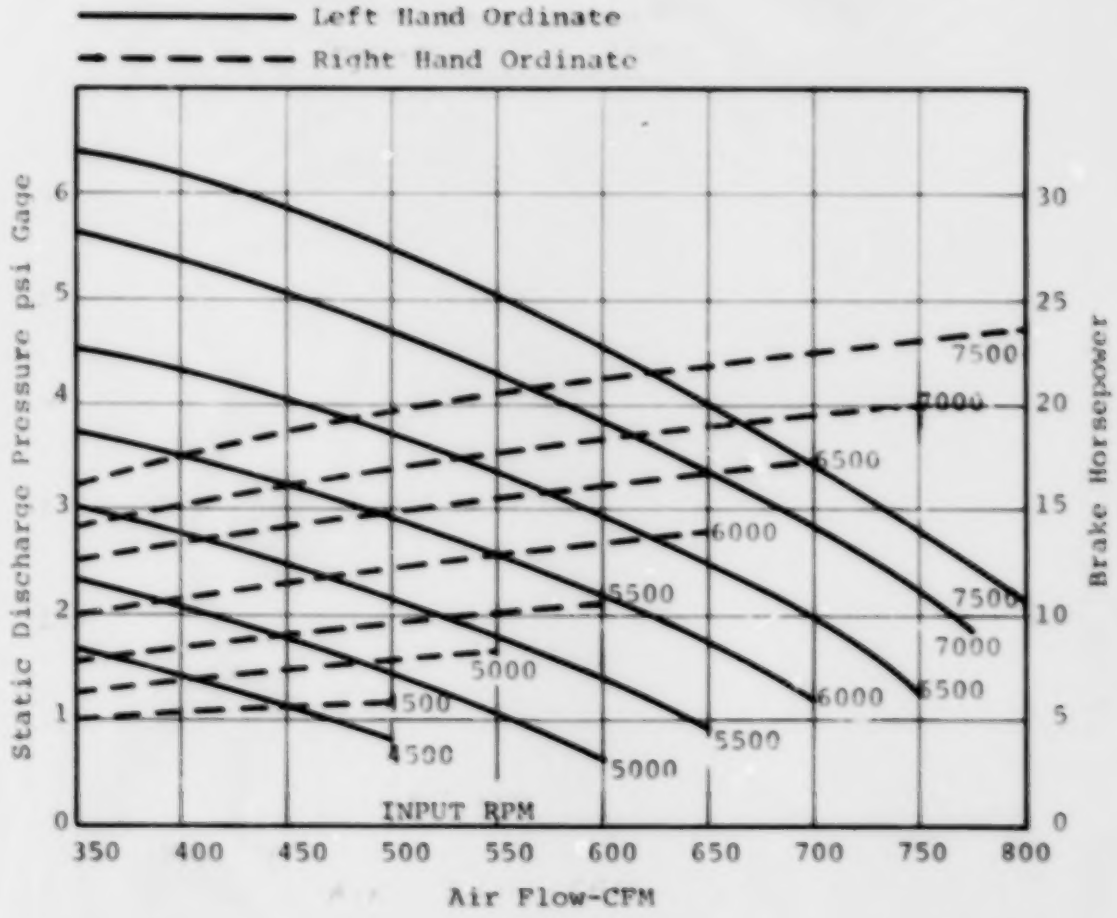


Figure 10. Performance curve for Paxton CB-80-H air blower

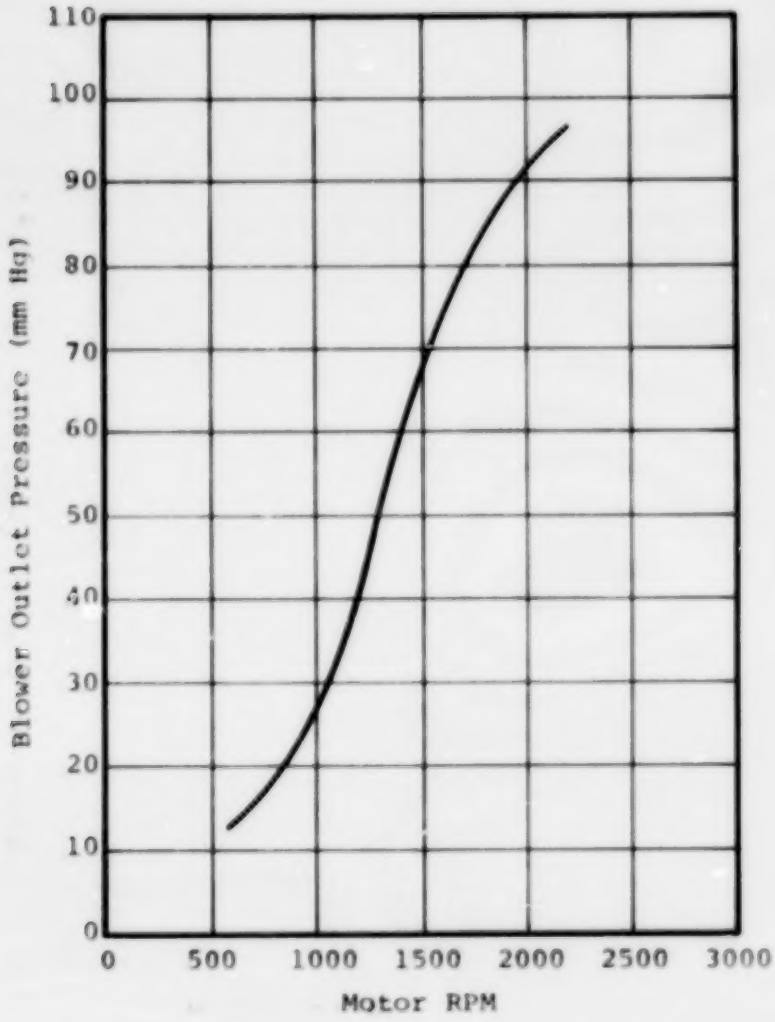


Figure 11. Paxton CB-80-H air blower calibration curve: motor revolutions per minute (RPM) versus blower outlet pressure (mm Hg)

choosing these particular designs are discussed below:
Rectangular slot nozzle (Figure 12) - This nozzle has a simple rectangular slot design and will be used as a standard to which the performance of the other nozzles will be compared.

Hypermixing nozzle (Figure 13) - This design consists of a series of alternating rectangular slots, where every other slot is directed upward along the coanda surface or downward on the water surface. It is believed that once the surface layer of water has been lofted into the air by the row of jets directed at the water surface the other series of jets will further break up the coarse droplets into a fine spray, thus facilitating the collection process.

Delta wing nozzle (Figure 14) - the delta wing inserts may be placed in the nozzle in a number of different ways - in a row, in an alternating fashion, etc. The purpose of the delta wing design is to facilitate in the formation of vortices which are shed in the direction of the air flow. These vortices will serve to loft and break up the water droplets into a fine spray.

Obstacle nozzle (Figure 15) - This nozzle consists of a series of obstacles placed in its exit plane. The obstacles generate a highly disturbed vortical flow just downstream of the nozzle exit. It is believed that the resulting flow will aid in disturbing the water surface so as to generate a fine water spray.

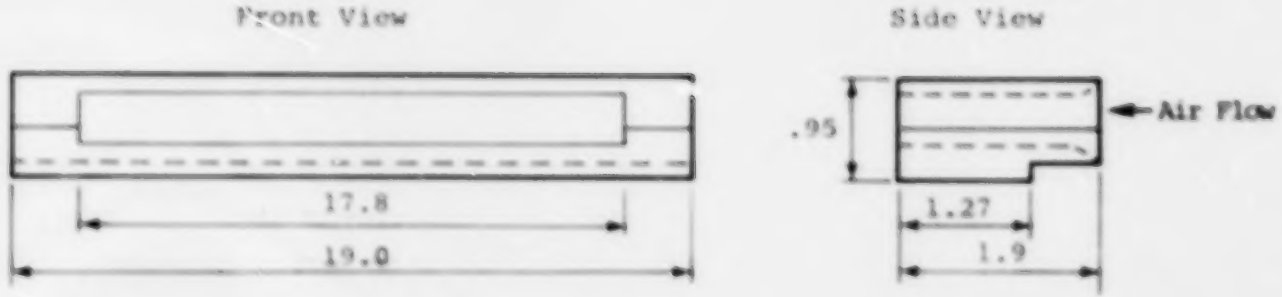
Description of Tests -

The tests reported upon here complete those associated with the investigation of the nozzle exit configuration, jet velocity and depth of nozzle submergence. These tests were conducted in the two-dimensional water flume shown in Figure 16 with the Paxton CB-80-H air blower unit.

In the first series of experiments, each of two jet nozzles were tested over a wide range of exit velocities, 65 to 135 m/sec, for a nozzle submergence depth (h) of zero. The nozzle submergence depth is the distance measured from the lower lip of the nozzle to the water surface. Therefore, a zero depth of submergence corresponds to the jet exiting tangential to the water surface. The primary quantity under investigation here was the angle that the spray makes with the undisturbed water surface. It was found that the water spray angle (measured clockwise from the surface of the water) was independent of the jet velocity for a given nozzle configuration. However, each nozzle had associated with it a unique spray angle, which is shown in Table 1.

The next set of experiments were conducted to determine the dependence of the water spray angle upon the nozzle submergence. Since it was found that the water spray angle was independent

Schematic D awin: of Nozzle Insert Location



Note: All Dimensions in cm

Figure 12. Schematic drawing of rectangular nozzle insert

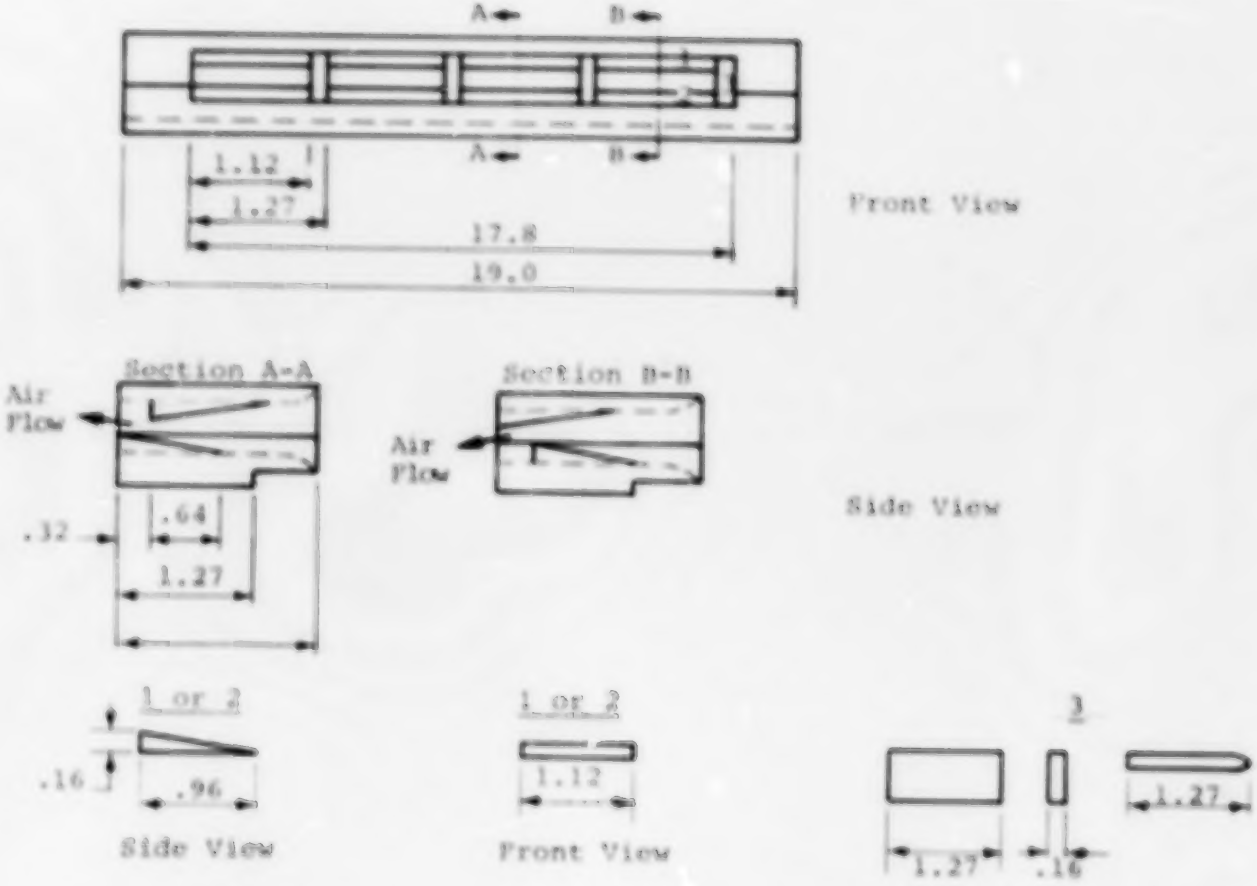
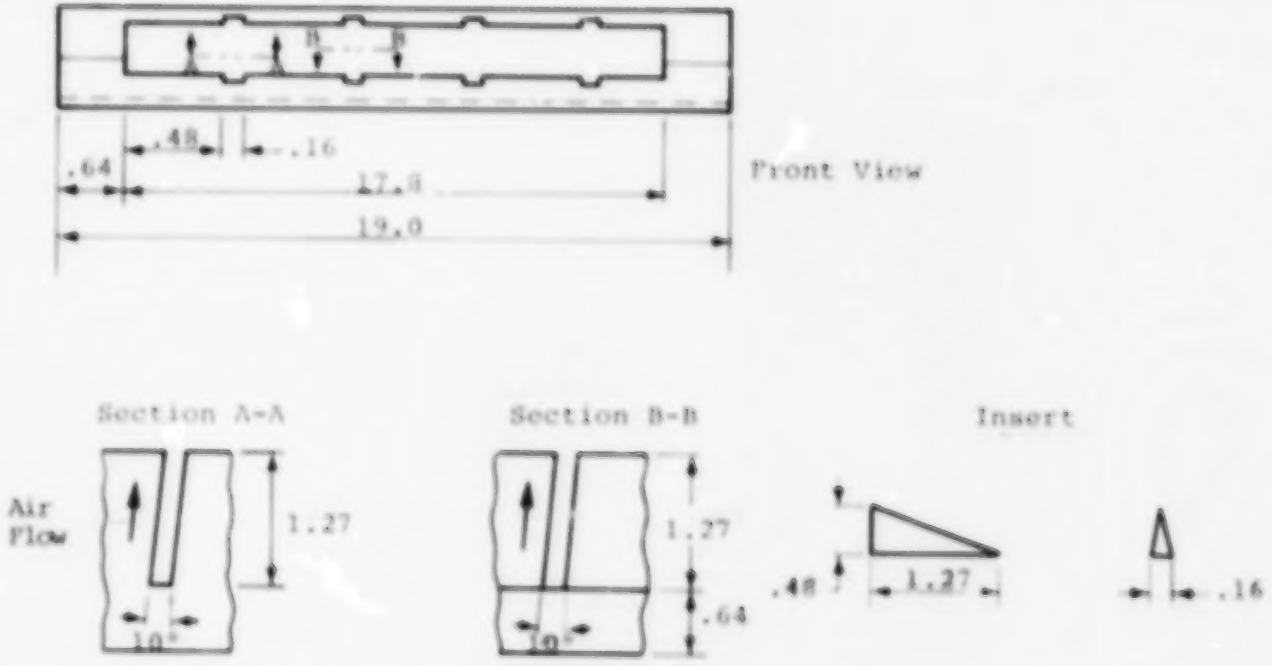
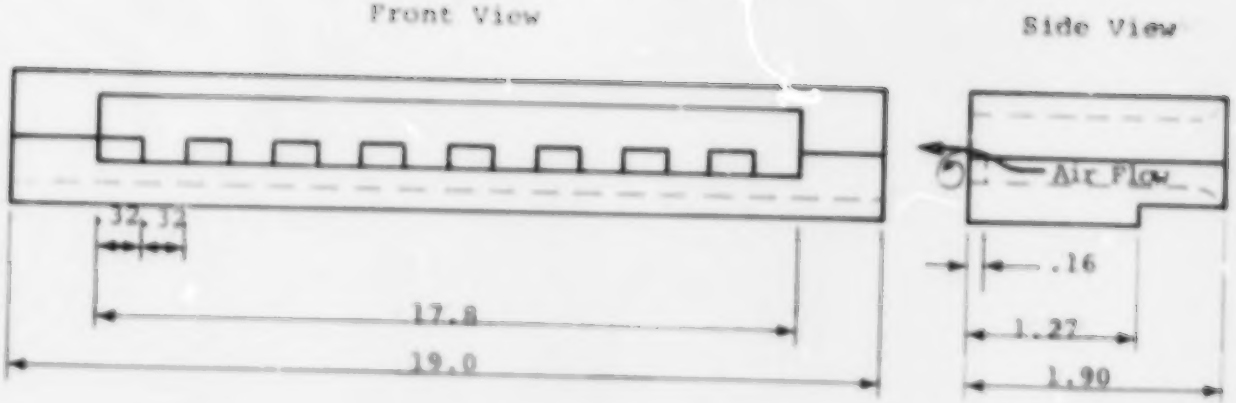


Figure 13. Schematic drawing of hypermixing nozzle insert



Note: All Dimensions in cm

Figure 14. Schematic drawing of delta wing nozzle insert



Note: All Dimensions in cm

Figure 15. Schematic drawing of obstacle nozzle insert

Figure 16. Photograph of two-dimensional water flume and Paxton CB-80-H air blower unit

Table 1. WATER SPRAY ANGLES FOR FOUR (4) NOZZLE EXIT CONFIGURATIONS

Jet Velocity Range 65 to 135 m/sec Nozzle Depth of Submergence, h=0 mm Water Velocity, 1.0 knot	
Nozzle Configuration	Spray Angle
Rectangular Slot	25°
Hypermixing	20.4°
Obstacle	20°
Delta Wing	31°

of jet exit velocity, these tests were performed at a jet velocity of approximately 85 m/sec. The results of these tests for all four of the nozzle configurations are shown in Figure 17. It can easily be seen that there is a strong dependence of water spray angle on nozzle submergence.

Although no quantitative measurements were made other than the spray angle, some interesting observations concerning the spray quality can be reported. It was found that the higher jet velocities increased the length of the spray trajectory as well as decreasing the droplet size. Moreover, for larger depths of submergence the height of the trajectory increased, whereas the length of the trajectory decreased while the droplet size increased. Finally, it was found that the finest droplets overall were produced by the obstacle and delta wing nozzles followed by the hypermixing and rectangular slot nozzles.

The results of these tests can be succinctly summarized as follows:

(1) The water spray angle is independent of jet velocity but is dependent upon nozzle configuration and nozzle depth of submergence.

(2) Higher jet velocities increased the length of spray trajectory and decreased water droplet diameter.

(3) Larger nozzle submergence increased the trajectory height, reduced its length and increased water droplet diameter.

(4) The finest water droplets were produced by the obstacle and delta wing nozzles followed by the hypermixing and rectangular slot nozzles.

Test Series 4

Based on the results of the previous tests, the obstacle nozzle was chosen to conduct the oil collection experiments. The experimental apparatus for these tests is shown in Figures 18a and b which reveal side and top views, respectively, of the two-dimensional water flume. The polyurethane foam collector consists of a plywood frame with a wire mesh backing to which the polyurethane foam pads are clipped. The collector has been placed at an angle of 45° to the surface of the water and about 30 cm downstream of the jet exit. The polyurethane foam sheets used for these tests measured 1.2 cm x 20 cm x 30 cm. In each test the jet exit velocity was approximately 85 m/sec and the water flow velocity in the flume was set at 1.0 knot. A discussion of the results from the most informative tests is presented below.

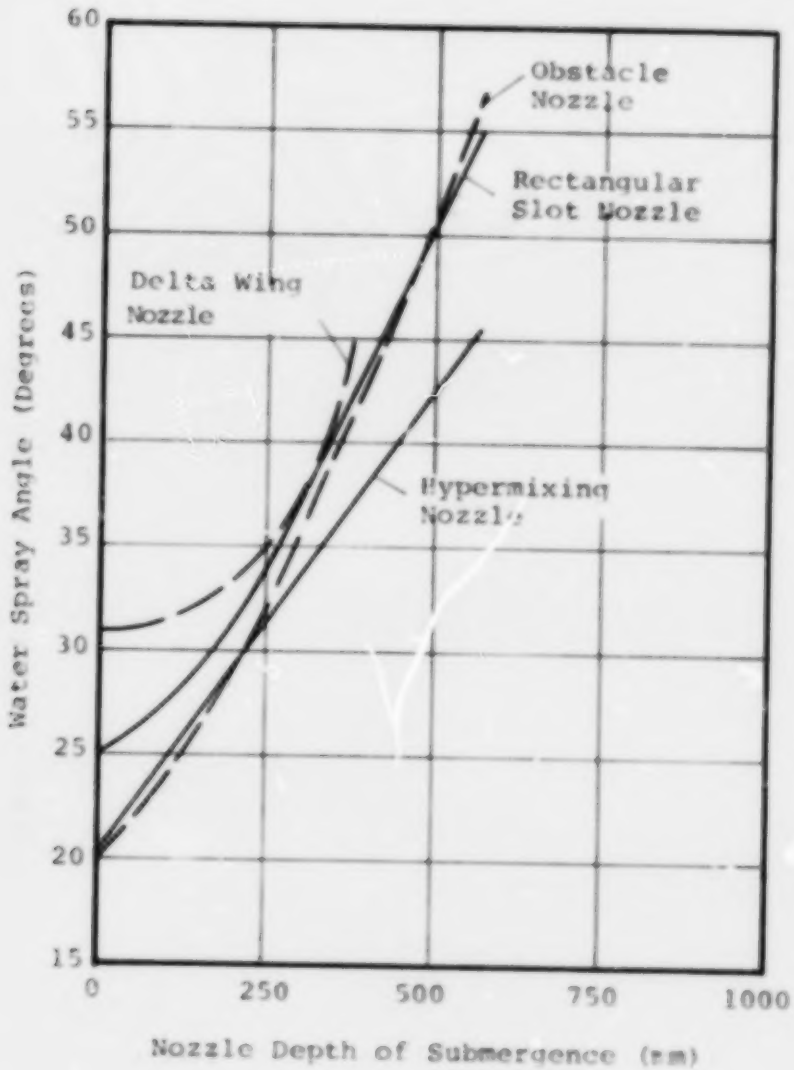


Figure 17. Graph of water spray angle (degrees) versus nozzle depth of submergence (mm) for four (4) nozzle exit configurations at constant velocity

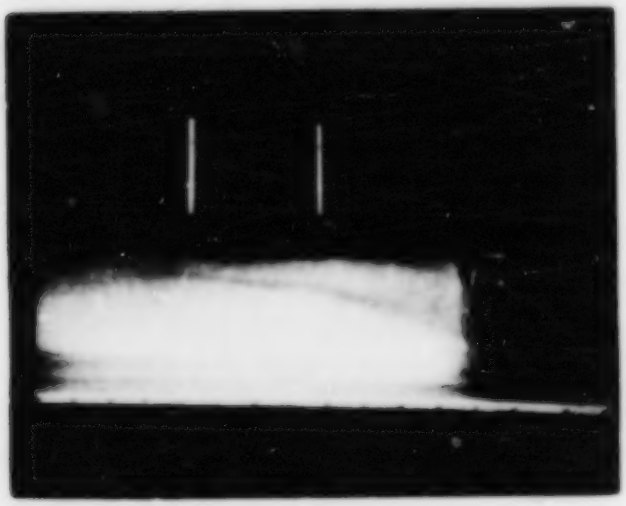


Figure 18a. Side view photograph of polyurethane foam collector prior to testing

Figure 18b. Photograph showing a top view of the two-dimensional water flume prior to a test

Test Number 1 -

Test conditions - 20 pores per inch (ppi) polyurethane foam used; blower RPM = 1,400; water height in flume = 5 cm; 100 milliliters of SAE 90 oil used.

Test summary - The water flow and air jet were turned on while the SAE 90 oil was poured onto the surface of the water downstream of the polyurethane collector. As the oil approached the region of influence of the jet, it was lofted into the air and onto the collector surface. The experiment lasted for about 30 seconds until almost all of the oil had disappeared. Upon squeezing the foam sheet it was determined that approximately 75% of the oil was recovered. However, the recovered oil was slightly emulsified. The emulsification process was hastened by the detergent nature of the oil used for this particular test.

Test Number 2 -

Test conditions - 60 ppi polyurethane foam used; blower RPM = 1,400; water height in flume = 5 cm; 100 milliliters of No. 2 fuel oil used.

Test summary - As the No. 2 fuel oil was poured onto the surface of the water at the downstream end of the tank, it began to emulsify almost immediately, forming a milky white, cloudy mixture in the water. This rapid mixing was the result of the high turbulence levels existing in the water at the point of injection of the oil - this is not to be expected under actual operating conditions. However, the sprayed oil/water mixture did adhere to the surface of the foam sheet but not very much oil (approximately 5%) was recovered in the process. Since the No. 2 fuel oil is highly sensitive to turbulent water conditions, it may always prove to be a problem in recovery, but only actual field tests will confirm this speculation. Improper cleaning of the tank might also have hastened the formation of the emulsion.

Test Number 3 -

Test conditions - 20 ppi polyurethane foam used; blower RPM = 1,400; water height in flume = 5 cm; 100 milliliters of No. 2 fuel oil used.

Test summary - This foam appeared to perform much better than the 60 ppi foam, since approximately 15% of the oil was recovered after squeezing of the foam was completed. Preliminary tests indicated that the ratio of oil to water in the recovered mixture was in the neighborhood of 1:1.5. Initial emulsification of the oil was still the major problem as it was in test number 2.

Test Number 4 -

Test conditions - 20 ppi polyurethane foam used; blower RPM = 1,400; water height in flume = 5 cm; 100 milliliters of Ward's heavy duty motor oil (SAE 10w-30) used.

Test summary - In this test approximately 30% of the oil was recovered; however, it was in an emulsified form with an oil/water ratio of approximately 1:1.5.

Test Number 5 -

Test conditions - 20 ppi polyurethane foam used; blower RPM = 1,400; water height in flume = 5 cm; 100 milliliters of No. 6 fuel oil used.

Test summary - Approximately 90% of the oil was recovered in this test with no noticeable emulsification occurring. Figures 19a and 19b are top and side view photographs of the polyurethane foam sheet, respectively, taken after the completion of the test. Very little of the oil originally on the surface of the water is seen to remain. The oil on the surface of the water that is visible in the photograph is that which has dripped off the polyurethane foam sheet after the test was performed.

Test Number 6 -

Test conditions - The final test was concerned with the broadcasting of chips of 20 and 60 ppi polyurethane foam and 100 ppi polystyrene foam on the surface of water and an attempt to recover the chips with the air jet apparatus. Blower RPM = 1,400; water height in flume = 5 cm; residual oil from all tests that remained on the surface.

Test summary - A number of the polystyrene chips were collected (several fell from the collector plate after the test - Figure 20), but not very many of the polyurethane chips were recovered. The main reason for this is that the polystyrene floated whereas the polyurethane sank beneath the water surface. However, the polyurethane chips contained significantly more oil than the polystyrene chips because the adsorptive properties of the former are better than the latter. This test also indicated that the air jet is affecting only the region of the water near the surface, otherwise more polyurethane chips would have been recovered.

The results of the foregoing oil collection tests were encouraging and are briefly summarized below:

(1) Approximately 75% of the SAE 90 oil was recovered in the test; however, some slight emulsification was noted.

Figure 19a. Top view of polyurethane foam collector after Test No. 5

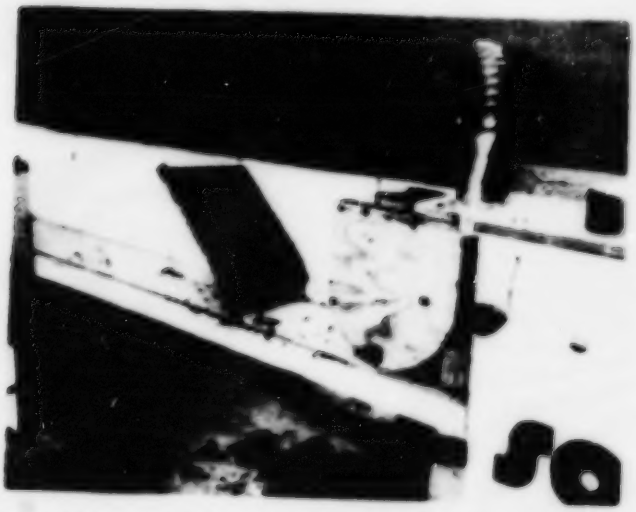


Figure 19b. Side view of polyurethane foam collector after Test No. 5

(2) Very light oils such as SAE 10w-30 and No. 2 fuel oil tend to emulsify (1:1.5 oil/water emulsification found here) and are sensitive in this respect to turbulent water conditions.

(3) Of the two polyurethane foams tested, the wider mesh 20 ppi foam was superior to the 60 ppi foam in adsorbing the oil. This is probably the result of a larger area of filtering surface presented to the oil/water spray by the former.

(4) The No. 6 fuel oil did not emulsify and was almost completely recovered.

(5) A mixture of 20 ppi and 60 ppi polyurethane foam chips collects more oil than 100 ppi polystyrene chips but the chips are not as efficiently removed from the water surface by the air jet because they sink below the water surface.

(6) After giving careful thought to the emulsification problem, it was decided that improper flume cleaning left residual detergent oil in the tank which aided the emulsification of some of the non-detergent oils used for these tests.

Figure 20. Collection of polyurethane and polystyrene foam chips in Test No. 6

POLYURETHANE FOAM ABSORPTION/ADSORPTION TESTS

A series of laboratory tests were conducted to determine the absorptive/adsorptive properties of polyurethane foam. A detailed description of these experiments appears in the Appendix. Several important questions regarding the properties of polyurethane foam were answered as a direct result of these experiments. The most important question that these experiments addressed was related to the oil retention characteristics of the polyurethane foam as a result of presoaking the foam in either oil or water. The test results indicated that there was no advantage to presoaking the polyurethane foam in either oil or water since its oil retention capacity remained unchanged. Furthermore, upon repeatedly soaking and squeezing the same foam sample ten times, it was found that its oil retention properties were unaltered. However, for longer periods of time it is expected that the foam will eventually deteriorate and its properties will change. It was also found that the ppi rating of the foam had a significant effect on the amount of oil retained. The larger (40 ppi) foam samples retained as much as six times the amount of No. 2 fuel oil as did the smaller (10 ppi) foam samples. These results had a significant impact on the interpretation of the data obtained during the prototype skimmer test program.

PROTOTYPE SKIMMER TEST PROGRAM

The prototype skimmer tests were conducted in the U.S. Environmental Protection Agency tow tank located in Edison, New Jersey. This tank is 30.5 m long, 3.65 m wide and 0.75 m deep. The test carriage is capable of towing models at speeds up to 4.05 knots and in waves not exceeding 30 cm in height. Figure 21 is a photograph of the wave generator which is located in the far end of the tank. This device consists of two triangular wedges which can be lowered at various frequencies, in or out of phase, into the water to produce waves. Figure 22 is a photograph of the wave absorbing beach which is located in the opposite end of the tank when installed. The beach consists of two sections of 25 - 2.5 cm x 2.5 cm x 3.65 m wood slats supported at the ends and in the middle by 4 - 7.5 cm x 7.5 cm x 1.8 m aluminum angles. In the 38 cm space separating the two sections are placed 6 - 7.5 m x 1.0 m wire mesh cages containing rubberized horse hair. The wave generator and beach have combined to produce reasonable non-reflecting waves of up to 30 cm in height.

Test Series 1

Preliminary tests were conducted for a variety of towing velocities and wave heights to explore the behavior of the skimmer over a wide range of test conditions. Two series of experiments were conducted; however, only qualitative data were obtained. The objective of the first test sequence was to determine the behavior of the skimmer under the influence of waves

Figure 21. Photograph of the U.S. Environmental Protection Agency 30.5 m long tow tank wave generator

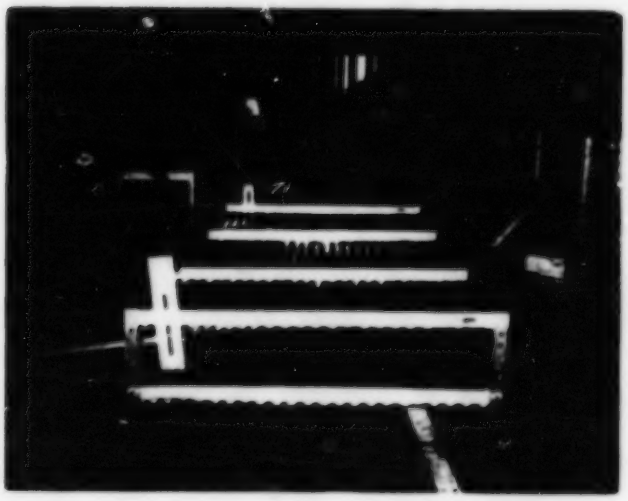


Figure 22. Photograph of the details of the beach

and currents without oil on the surface of the water. In the second series, Venezuelan crude oil was spread over the surface of the water and attempts at recovery were made.

The carriage used to tow the skimmer down the tank had a variable speed between 0 and 4.05 knots. Three speeds representative of this range were chosen to conduct the tests; they were 1.4, 3.25 and 4.05 knots. The total distance through which the carriage was towed was approximately 18.25 m - the first 4.55 m of which was devoted to the acceleration of the test device. Thus, actual test times for the towing velocities listed above were 28, 13 and 10 seconds, respectively. In addition, the angle that the air jet made with respect to the undisturbed surface of the water was variable between +4.5° and -3.0°. The positive angle refers to the jet directed into the water. A setting of +1.0° was used throughout the test sequence. One final parameter was variable on the test device - the velocity of the air jet. This velocity was set at approximately 75 m/sec for this series of tests. The wave generator was capable of establishing waves whose height did not exceed 30 cm; however, the range used for these tests was between 7.5 and 22.5 cm.

The primary objective of the first test series was to establish the behavior of the device for different speeds and wave conditions. With no waves and at speeds not exceeding 3.25 knots, the skimmer developed a generally fine, uniform spray across the 61 cm width of the device. However, above 3.25 knots, bow waves generated by the flotation pontoons, which were suspended from the sides of the skimmer began to push a great deal of water into the region of the air jet. This situation prevented the air jet from developing a fine, uniform spray as experienced during the lower-velocity tests. It was then decided that new pontoons would be required (having additional flotation as well). Moreover, these pontoons would be suspended sufficiently far from the sides of the skimmer (approximately one pontoon width) in order to prevent its bow wave from interfering with the flow in the vicinity of the air jet. The results from a number of repetitive tests confirmed that 3.25 knots would be the maximum speed attainable with the current flotation system. Therefore, the following two wave tests were conducted at that speed.

In the first test, 10 cm high waves, having a wavelength of approximately 4.5 m were established. The skimmer appeared to ride partially through and over the waves, the spray remaining uniform across the device at all times. In fact, very little if any difference between this test and that described earlier without waves was noted. In order to test at the other end of the spectrum, 22.5 cm high waves, having a wavelength of 3.5 m were generated. The device was again towed through the wave system at 3.25 knots. Some difficulty was observed in generating a fine, uniform spray as the device rose through the trough of the wave. Perhaps this was the result of insufficient

skimmer flotation (slight nose heaviness), causing the device to dive into the waves rather than following them. In summary, the results of these tests were encouraging since only minor problems concerning the flotation system were encountered.

The only difference between the first and second test sequences was the addition of oil to the surface of the water. For these tests, Venezuelan crude oil was spread over the surface of the water (approximately 560 gms of oil were used to produce a uniform film over a 75 m^2 region of the tank - this is equivalent to an oil film thickness of approximately 0.1 mm. Three tests were conducted at a towing speed of 3.25 knots and at wave heights of 0, 7.5 and 15 cm. In each test, a uniform oil/water spray was generated and a rectangular sheet (61 cm x 30 cm) of 20 ppi polyurethane foam, at an angle of 45° to the surface of the water, was used to intercept and collect the spray. Figure 23 is a photograph of the skimmer used for these tests. In each test, oil was recovered; however, the quantity was not measured. The purpose of these tests was to explore (within the capabilities of the test facility) the range of conditions under which oil recovery was possible. The results of these tests indicate that the skimmer can operate over the entire range of conditions that the test facility can produce. The only question that now remains is how much oil can be collected. This question was addressed in test series 2 through 4.

Figure 23. Photograph of the first 61 cm wide surface effects skimmer model connected to tow carriage

Test Series 2

The objective of these tests was to determine the amount of oil collected by the prototype skimmer model under the test conditions described in test series 1. The skimmer model used for these tests is shown in Figure 24. A rotating polyurethane foam belt was added to the skimmer model for these tests. The rotating belt system is composed of three rollers, only one of which has a positive drive. The remaining two rollers squeeze and guide the polyurethane foam sheet. The new pontoons for the skimmer are shown in Figure 24; each pontoon was manufactured from 26.25 cm diameter polyvinylchloride (PVC) pipe and the nose and rear inserts are composed of balsa wood. The pontoons are adjustable in both the vertical and horizontal directions so that the prototype skimmer can be properly positioned in the water. The oil distribution system is shown in Figure 25, and is composed of a 6.5 cm diameter aluminum cylinder with eleven (11) equally spaced holes (4 cm on center). The size of the holes are adjustable by placing an aluminum strip containing eleven (11) smaller holes over the original series of holes. In this manner, different oil flow rates and viscosities can be accommodated by the oil distribution system. Once the test carriage is in motion, the aluminum cylinder is rotated 180° so that the holes point downward to allow the oil to flow onto the surface of the water. In the present configuration, the oil spreads laterally over the surface of the water and fills the 61 cm wide capture region of the skimmer.

For the present series of tests, the polyurethane foam belt was rotated at a speed of 6 m/min and the forward velocity of the skimmer was set at 3.25 knots. The air jet nozzle was submerged about 1.5 cm below the water surface. This submergence depth was chosen (from the results of previous tests) as being that which develops a reasonable amount of spray for the power expended by the air jet with a minimum of water vortex formation near the nozzle exit plane. The air jet velocity used for these tests was 75 m/sec and Venezuelan crude oil was deposited on the water surface at the rate of 2.9 gms/sec. Waves were not present for this first attempt at the quantitative recovery of oil from the surface of the water. The test duration was approximately 30 seconds from acceleration through deceleration of the skimmer, and the total amount of oil deposited on the surface of the water was 87 gms. The foam belt weighed 326 gms prior to the test and after squeezing the water from the belt after the test it weighed 382 gms. It was deduced that the difference of 382 - 326 = 56 gms was due to the oil recovered during the experiment. This quantity of oil results in an oil collection efficiency of 56/87 = 64.5%. Figure 26 is a photograph of the rotating polyurethane foam belt removed from the skimmer after completion of the aforementioned test.

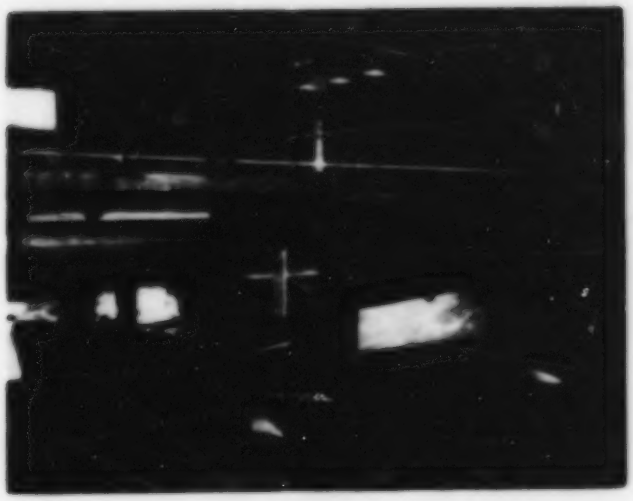


Figure 24. Photograph of the final 61 cm wide surface effects skimmer model after testing with Venezuelan crude oil

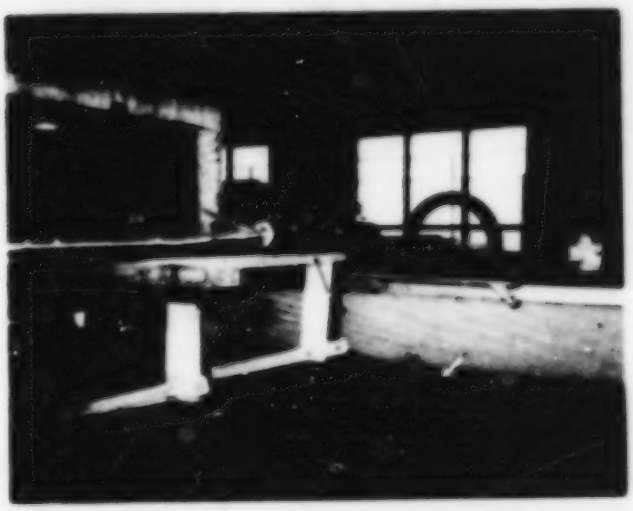


Figure 25. Photograph of the oil distribution system used during the prototype surface effects skimmer test program

Figure 26. Photograph of the rotating belt of polyurethane foam after completion of test with Venezuelan crude oil

Several other tests were conducted with the identical test conditions; however, inconsistent results were obtained. The results indicated that anywhere between 0 and 100% of the oil was recovered. However, it is believed that the figure of 64.5% is representative of the actual recovery efficiencies attainable with the present skimmer model. In order to substantiate this statement, it was thought that a longer run time would be required to collect a sufficient quantity of oil so that the test results would be more meaningful. Longer run times at the towing speeds of interest here (3.25 knots) can only be achieved by making several identical runs before extracting and weighing the foam belt. By conducting tests in this manner some of the oil not recovered during previous tests has a second opportunity for recovery. However, this latter quantity of oil has spread over the entire tank in between tests and only a small portion is available for recovery during the next test. The test conditions just described are less than ideal; however, it is the only available way in which to generate the longer test times required for this experiment.

Test Series 3

The objective of this test series was to confirm the adequacy of the aforementioned test procedure in obtaining realistic oil collection efficiencies for the prototype skimmer model. In order to achieve this objective, three (3) sets of tests were performed; each set consisted of five (5) separate experiments

run in succession. At the beginning of each set of tests a dry polyurethane foam belt was used on the prototype skimmer model. During the first test set, the polyurethane foam belt was removed from the skimmer for weighing after each experiment; however, the belt was not wrung out between each experiment. In this way, some estimate of the rate of oil recovery as well as the rate of replacement of water with oil in the foam belt could be determined. During the last two sets of tests, a small hydrofoil was placed below the nozzle; however, in these latter tests the foam belt was not removed after each individual experiment.

The three test sets (described below) were all performed with Venezuelan crude oil and the skimmer was towed at a velocity of 3.25 knots in calm water conditions. The 20 ppi polyurethane foam belt was rotated at a velocity of 6 m/min, and each individual experiment's duration was approximately 18 seconds.

During the first test set, the foam belt was removed after each experiment and weighed as discussed earlier. The results of this test are presented below in Table 2.

Table 2. OIL COLLECTION EFFICIENCY TEST DATA FOR INDIVIDUAL TEST SEQUENCES WITHOUT THE USE OF THE HYDROFOIL - TEST SET NUMBER 1

Test No.	Quantity of Venezuelan crude oil deposited on water surface (gms)	Test duration (seconds)	Foam belt weight after each experiment (gms)
1	169	22	1,381
2	115	15	1,27[illegible]
3	115	15	1,280
4	154	20	1,261
5	154	20	1,278
TOTALS	706	92	1,278

The data in Table 2 indicate that after the first test the weight of the foam belt remains essentially constant; it is believed that the oil in each subsequent test is replacing the water in the foam belt. After test number 5, in order to obtain an estimate of the amount of oil recovered by the foam, the following was done: the foam was carefully squeezed to remove any water -

this process resulted in 533 grams of water removed from the foam. Since the total weight of the foam after squeezing was 745 grams and since the foam's initial weight was 330 grams, the remainder (745-330 = 415 grams) represents the oil recovered. The ratio of 415/706 = .59 is the oil collection efficiency of the skimmer.

Prior to the second test set, the bottom brace of the rotating polyurethane foam belt was removed because it was interfering with the oil flow upstream of the air jet. In addition, a hydrofoil (Figure 27) was placed across and below the entire 61 cm width of the air jet nozzle with its maximum chord position at the nozzle exit. The primary reasons for employing the hydrofoil were to prevent the formation of a strong water vortex in the vicinity of the air jet nozzle and to direct the oil/water flow to the region of influence of the air jet. Therefore, the possibility of diverting the oil/water flow under the skimmer model (by the vortex) and away from the region of influence of the air jet is greatly minimized. The results of this test are summarized in Table 3.

Table 3. OIL COLLECTION EFFICIENCY TEST DATA FOR SEQUENCES WITH THE USE OF THE HYDROFOIL - TEST SET NUMBER 2

Test No.	Quantity of Venezuelan crude oil deposited on water surface (gms)	Test duration (seconds)	Foam belt weight after each experiment (gms)
1-5	691	90	1,335

The foam belt used for the second test set was initially dry and weighed 330 gms. After the second test set was completed, 550 gms of water were removed by squeezing the foam belt. The weight of the oil captured in the foam was 1,335 - 330 - 550 = 455 gms. Therefore, the oil collection efficiency is 455/691 = .66.

In order to confirm this last result, a third test set (identical to the previous test set) was performed. The results of these experiments are shown in Table 4.

Table 4. OIL COLLECTION EFFICIENCY TEST DATA FOR SEQUENCES WITH THE USE OF THE HYDROFOIL (REPEAT OF TEST SET NUMBER 2 REPORTED IN TABLE 3) - TEST SET NUMBER 3

Test No.	Quantity of Venezuelan crude oil deposited on water surface (gms)	Test duration (seconds)	Foam bel weight after each experiment (gms)
1-5	691	90	1,248

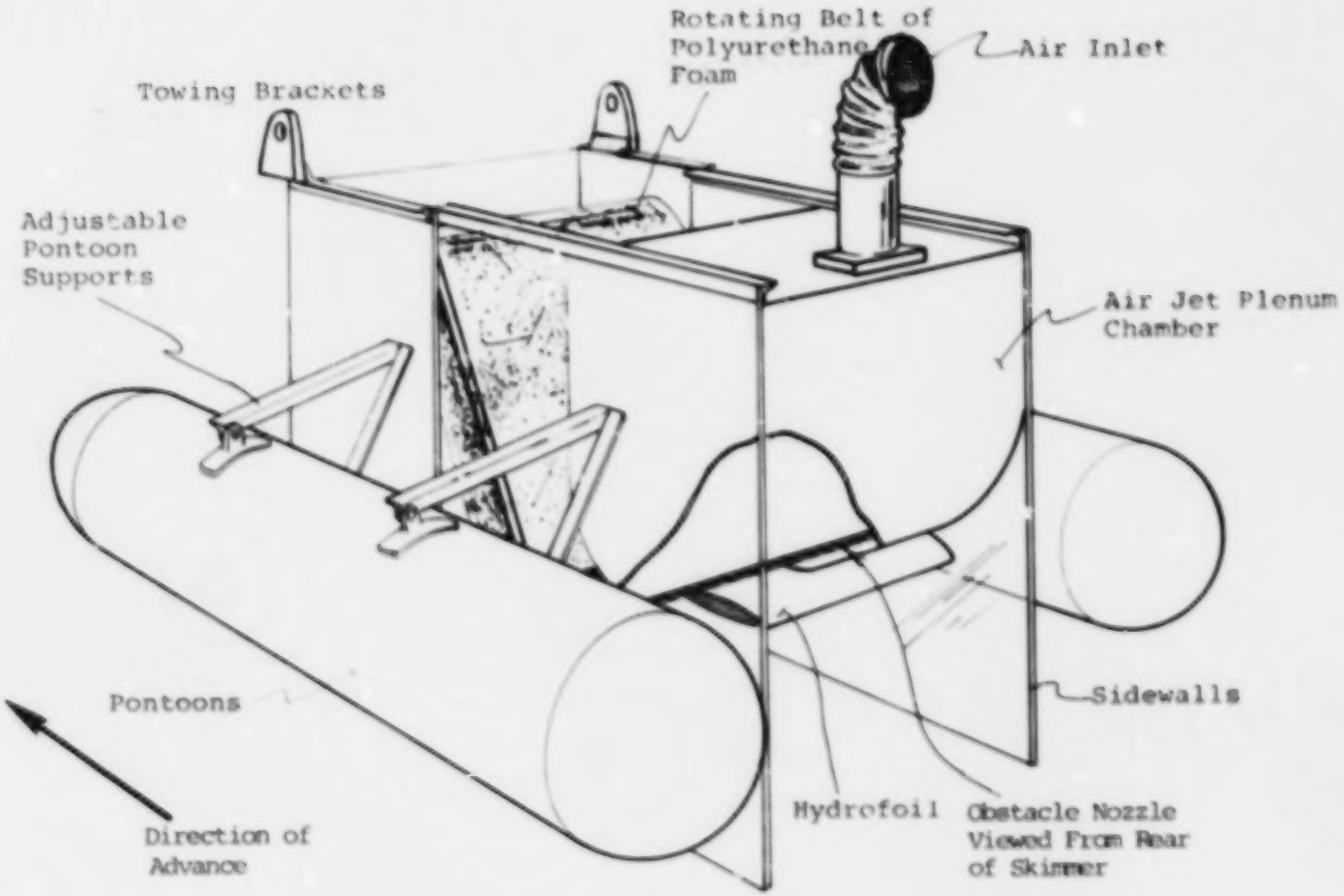


Figure 27. Schematic drawing of the final version of the surface effects skimmer model with the hydrofoil installed

The foam belt was initially dry and weighed 330 gms. After the test set was completed, 475 gms of water were squeezed from the belt. Therefore, 1,248 - 330 - 475 = 443 gms of oil remained in the foam and the resultant oil collection efficiency was 443/691 = .64.

The results of these tests have conclusively shown that the oil collection efficiency of the surface effects skimmer is in the neighborhood of 65% for the heavy Venezuelan crude oil. It also appears that the hydrofoil, installed in the manner discussed previously, improves the oil collection efficiency by about 10%. It remains to test the prototype skimmer over a wider range of test conditions to determine its behavior in waves and with lighter oils. These latter experiments comprise the last tests performed during this program.

Test Series 4

During test series 3, an experimental procedure was developed that yielded sufficiently repeatable oil collection efficiency data. In this test series, the same procedure was used; however, the scope of the test conditions was expanded.

Tests were conducted in calm, wavy and choppy water conditions with two types of oil, Venezuelan crude and No. 4 distillate fuel oil. Moreover, three types of polyurethane foam were also employed, 20, 40 and 60 ppi foam. In this manner, a broad spectrum of test conditions could be investigated in relatively few experiments. Each test consisted of four (4) or five (5) individual experiments run in succession and a new dry foam belt was used at the beginning of each test. The towing velocity of the skimmer and rotation speed of the polyurethane foam belt were kept constant during the tests at 3.25 knots and 6 m/min, respectively.

A summary of the data obtained for each of the six (6) tests performed in test series 4 and two (2) of the tests conducted in test series 3 is shown in Table 5. The data from test series 3 have been included here for comparative purposes and appear under test numbers 1 and 2, whereas the data from test series 4 are included in tests 3 through 8.

A comparison of the results of tests 1 and 2 shows that the only difference between them was the presence of the hydrofoil in test 2. The hydrofoil prevented oil from escaping the region of influence of the air jet and resulted in a 10% increase of the skimmer's oil collection efficiency. Therefore, the hydrofoil was employed in the remainder of the test program.

The results of tests 3, 4 and 5 clearly show the importance of the type of foam on the collection efficiency in calm water. For practical purposes, the 20 and 40 ppi foams yielded the

Table 5. SUMMARY OF SIGNIFICANT SURFACE EFFECTS SKIMMER PROTOTYPE TEST DATA

	SERIES 3		SERIES 4					
			TEST NUMBER					
Measured Parameter	1	2	3	4	5	6	7	8
Water Condition	Calm	Calm	Calm	Calm	Calm	Smooth Waves 13.75 cm crest; 4.5 to 6 m length	Smooth Waves 13.75 cm crest; 4.5 to 6 m length	Choppy Waves 22.5 cm crest; 2.5 to 6 m length
Test Duration (sec)	92	90	80	90	80	80	80	80
Type of Polyurethane Foam	20 ppi	20 ppi	20 ppi	40 ppi	60 ppi	40 ppi	20 ppi	40 ppi
Type of Oil	V. crude	V. crude	No.4 dist.	No.4 dist.	No.4 dist.	No. 4 dist.	V. crude	No. 4 dist.
Hydrofoil Used	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Dry Foam Belt Weight (gms)	330	330	326	354	393	360	321	361
Weight of oil + water + belt after test sequence (gms)	1278	1330	1423	1450	1817	1773	1183	1546

(Table Continued On Next Page)

Table 5 (Continued)

	SERIES 3		SERIES 4					
			TEST NUMBER					
Measured Parameter	1	2	3	4	5	6	7	8
Weight of water squeezed from belt after test (gms)	533	550	725	663	945	890	503	718
Weight of belt after squeezing out water (gms)	745	880	698	787	872	883	680	828
Weight of oil recovered (gms)	415	455	375	432	477	528	359	469
Weight of oil spread on water surface during test (gms)	706	691	852	959	852	852	432	852
Oil collection efficiency	.59	.66	.44	.45	.56	.62	.83	.55

same efficiency. However, the use of the 60 ppi foam with the light No. 4 distillate fuel oil resulted in approximately a 25% increase in oil collection efficiency. Moreover, when smooth waves were present and the 40 ppi foam was used with the No. 4 distillate fuel oil (test 6), a 30% increase in collection efficiency (over the case without waves - test 4) was obtained.

It was concluded that in the presence of waves the skimmer air jet nozzle was thrust deeper into the water, resulting in a larger fraction of the oil in the oil/water spray. This same result was obtained for the case of the Venezuelan crude oil (tests 2 and 7) in which a 30% increase in oil collection efficiency was also obtained when waves were present.

In comparing the results of test numbers 4, 6 and 8, it can easily be seen that the presence of very choppy water reduced the collection efficiency for the No. 4 distillate fuel oil below that obtained for smooth waves, but above the calm water recovery rate. In the case of choppy waves (high frequency wavelets) the skimmer flotation system cannot accommodate to the surface movement as it can for the situation where low frequency waves are present. This results in the lower oil collection efficiency reported here.

The following general conclusions have been reached as a result of the prototype skimmer test program:

(1) This skimmer concept works only at speeds over water above 1.0 knot.

(2) At a skimmer speed of 3.25 knots:

(a) The presence of waves (high or low frequency) greatly improves the oil collection efficiency for both of the test oils broadcast on the surface of the water.

(b) The presence of very chopoy water reduces the oil collection efficiency below that obtained in smooth waves but above that reported for the calm water tests.

(c) Increasing the ppi of the foam from 20 or 40 to 60 results in improved oil collection efficiencies for the No. 4 distillate fuel oil.

(d) Higher oil collection efficiencies are generally associated with the more viscous oils; however, the optimum ppi foam may not have been used for the tests with the No. 4 distillate fuel oil.

SECTION VI

BIBLIOGRAPHY

The following reports are not specifically referenced in the document; however, they provide useful background reading.

1. University of California, Santa Barbara, California, "Santa Barbara Oil Pollution, 1969," Water Pollution Control Research Series, 15080 DZR, November 1970.

2. Alpine Geophysical Associates, Inc., "Oil Pollution Incident Platform Charlie," Main Pass, Block 41 Field, Louisiana, Water Pollution Control Research Series, 15080 FTU, May 1971.

3. Maine Port Authority, "Testing and Evaluation of Oil Spill Recovery Equipment," Water Pollution Control Research Series, 15080 DDZ, December 1970.

4. Fay, James A., "Oil Spills: The Need for Law and Science," Technology Review, Vol. 72, No. 3, January 1970.

5. Cross, Ralph H. and David P. Hoult, "Collection of Oil Slicks," ASCE National Meeting on Transportation Engineering, Boston, Mass., July 13-17, 1970, Preprint No. 1236.

6. Fay, James A., "Physical Processes in the Spread of Oil on a Water Surface," Fluid Mech. Lab., Dept. of Mech. Engr., MIT, Cambridge, Mass.

7. Fay, James A., "The Spread of Oil Slicks on a Calm Sea," Fluid Mechanics Laboratory, Publication No. 69-6, Department of Mech. Engr., MIT, Cambridge, Mass.

8. Hoult, David P., "Containment and Collection of Oil Slicks," Fluid Mech. Laboratory, Publication No. 69-8, Department of Mech. Engr., MIT, Cambridge, Mass.

9. Hoult, David P., "Containment of Oil Spills by Physical and Air Barriers," STOP Pollution Series, MIT, Cambridge, Mass.

10. Hoult, David P. and Walter Suchon, "The Spread of Oil in a Channel," STOP Pollution Series, MIT, Cambridge, Mass.

11. Pacific Northwest Laboratories, Battelle Memorial Institute, "Recovery of Oil Spills Using Vortex Assisted Airlift System," Water Pollution Control Research Series, 15080 DJM, July 1970.

12. The Garrett Corporation, "Oil/Water Separation Systems with Sea Skimmer," Water Pollution Control Research Series, 15080 DJP, October 1970.

13. National Oil Recovery Corporation, "Conversion of Crankcase Oil Waste into Useful Products," Water Pollution Control Research Series, 15080 DBO, March 1971.

14. Edison Water Quality Laboratory, "Chemical Treatment of Oil Slicks," Water Pollution Control Research Series, DAST-18.

15. Envirogenics Co., Aerojet General Corp., "Feasibility Analysis of Incinerator Systems for Restoration of Oil Contaminated Beaches," Water Pollution Control Research Series, 15080 DXE, November 1970.

16. Edison Water Quality Laboratory, "Oil Dispersing Chemicals," Water Pollution Research Series, ORD-3.

17. Melpar, "Oil Tagging System Study," Water Pollution Control Research Series, 15080 DJO, May 1970.

18. URS Research Co., "Evaluation of Selected Earthmoving Equipment for the Restoration of Oil-Contaminated Beaches," Water Pollution Control Research Series, 15080 EOS, October 1970-71.

19. Atlantic Research Corp., "Recovery of Floating Oil Rotating Type Disk Skimmer," Water Pollution Research Control Series, 15080 FWN, July 1971.

20. University of New Mexico, "Floating Oil Recovery Device," Water Pollution Control Research Series, 15080 FWO, February 1971.

21. Jaumette, A., et al., "Cushion Mechanics of a Peripheral Jet ACV in Hovering Flight Over Water," Hovering Craft and Hydrofoil, Vol. 11, No. 7, April 1972.

22. Hope-Gill, C.D., "Static Water Spray Tests with Simulated Peripheral Air Jets," Bell Aerospace Company Report No. 9500-920185, November 1970.

23. Environmental Protection Agency, Office of Water Programs, "Control of Oil and Other Hazardous Materials," December 1971.

24. Agnew, R. W., "A Free Floating Endless Belt Oil Skimmer," EPA-R2-72-006, August 1972.

25. Cochran, R. A. et al., "An Oil Recovery System Utilizing Polyurethane Foam - A Feasibility Study," EPA-670/2-73-084, October 1973.

26. Gumtz, G. D. and T. P. Meloy, "Oil Recovery System Using Sorbent Material," EPA-670/2-73-068, September 1973.

27. Miller, E. et al., "Development and Preliminary Design of a Sorbent-Oil Recovery System," EPA-R2-73-156, January 1973.

28. Henager, C. H. and J. D. Smith, "Concept Evaluation: Recovery of Floating Oil Using Polyurethane Foam Sorbent," EPA-R2-72-049, September 1972.

29. Sartor, J. D., et al., "Oil/Sorbent Harvesting System for Use on Vessels of Opportunity," EPA-R2-73-166, April 1973.

30. Schatzberg, Paul and K. V. Nagy, "Sorbents for Oil Spill Removal," Proceedings of Joint Conference on Prevention and Control of Oil Spills, Washington, D.C., June 1971.

SECTION VII

LIST OF PUBLICATIONS

Freestone, F. J., R. A. Anderson, and N. P. Trentacoste, "USEPA Research in High Speed Devices for the Recovery of Thin Oil Spills," Conference on the Prevention and Control of Oil Pollution, March 25-27, 1975, San Francisco, California.

SECTION VIII

APPENDIX

POLYURETHANE FOAM ABSORPTION/ADSORPTION TESTS

The primary reason for performing the polyurethane foam absorption/adsorption tests was to shed some light on the oil retention characteristics of the foam. In particular, an answer to the question of whether or not presoaking the polyurethane foam in oil or water had any effect on its oil retention capacity was sought. Two separate experiments were performed, which in combination, answered this question. The first experiment was performed during the early part of the program. However, upon reviewing the data there appeared to be some doubt as to the conclusions that could be drawn from the test results. Therefore, a second experiment was performed after the completion of all other tests. The latter experiment in combination with the first one answered the important question posed earlier. The remainder of this section is devoted to a detailed description of the two experiments and the conclusions that were drawn from the data.

In order to determine the quantity of oil and water that the polyurethane foam can absorb/adsorb under a given set of conditions, a series of laboratory experiments were devised and performed. These experiments were carried out as follows: samples of the polyurethane foam were cut to a uniform size and weighed, then dipped into a beaker containing oil (water) for about 20 seconds. The samples were then extracted and allowed to drain until dripping essentially stopped. The samples were then squeezed for 20 seconds and the oil (water) was recovered and measured. The foam sample was subsequently weighed to determine how much oil (water) remained in the foam. This procedure was repeated in reverse so that the water soaked samples were dipped in oil and the oil soaked samples were dipped in water. The polyurethane foam used for these tests had a 20 ppi rating and was cut into two (2) sample sizes: 7.62 cm x 7.62 cm x 1.9 cm; and 4.44 cm x 4.44 cm x 1.9 cm. Two types of oils were also used. No. 2 and No. 6 fuel oil. The results of these tests are reported

in mean values of the quantities

$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} X_i$ and the mean squared deviation $\sigma^2 = \frac{1}{N}\sum_{i=1}^{N} (X_i - \bar{X})^2$.

Test Parameters

Fluid densities - water at 22°C = 1.0 gm/ml
No. 2 fuel oil at 22°C = 0.824 gm/ml
No. 6 fuel oil at 42°C = 0.932 gm/ml

Foam dimensions - 7.62 cm x 7.62 cm x 1.9 cm sample
volume = 111.1 cm^3
surface area = 174.2 cm^2
volume/surface area = .64 cm

4.44 cm x 4.44 cm x 1.9 cm sample
volume = 37.7 cm^3
surface area = 73.2 cm^2
volume/surface area = .51 cm

$\frac{\text{Surface Area (7.62 cm sample)}}{\text{Surface Area (4.44 cm sample)}} = 2.38$

The results of the tests are summarized in Tables 6 through 12.

Some very interesting results were obtained from a comparison of test series 1 and 4, and 2 and 3. These results are summarized below:

Series 1 and 4

The amount of water squeezed from the foam/the amount of water remaining in the foam (Wo/Wi)

Series 1 - Wo/Wi = 10.92/3.69 = 2.96
Series 4 - Wo/Wi = 9.78/3.37 = 2.90

Series 2 and 3

The amount of oil squeezed from the foam/the amount of oil remaining in the foam (Oo/Oi)

Series 2 = Oo/Oi = 4.25/2.66 = 1.60
Series 3 - Oo/Oi = 3.96/2.45 = 1.62

Table 6. SERIES 1 - WATER ABSORPTION TESTS WITH 20 ppi POLYURETHANE FOAM SAMPLES CUT INTO 7.62 cm x 7.62 cm x 1.9 cm STRIPS (10 SAMPLES USED)

	Foam weight in gms. before wetting	Foam weight in gms. after squeezing	Weight of water in gms. remaining in foam after squeezing	Weight of water in gms. squeezed from foam
$\bar{X}$	3.24	6.93	3.69	10.92
σ^2	.0024	.2221	.2567	.009

Table 7. SERIES 2 - NO. 2 FUEL OIL ABSORPTION TESTS WITH 20 ppi POLYURETHANE FOAM SAMPLES CUT INTO 7.62 cm x 7.62 cm x 1.9 cm STRIPS (10 SAMPLES USED)

	Foam weight in gms. before wetting	Foam weight in gms. after squeezing	Weight of oil in gms. remaining in foam after squeezing	Weight of oil in gms. squeezed from foam
$\bar{X}$	3.22	5.88	2.66	4.25
σ^2	0.0016	0.0176	0.0394	0.0084

Table 8. SERIES 3 - USING FOAM SAMPLES ORIGINALLY DIPPED IN WATER (SERIES 1), NOW DIP IN NO. 2 FUEL OIL (8 SAMPLES USED)

	Foam weight in gms.	Weight of water in gms. in foam before testing	Total weight of oil/water & foam in gms. after squeezing	Weight of oil in gms. squeezed from foam	Weight of water in gms. squeezed from foam	Weight of water in gms. remaining in foam	Weight of oil in gms. remaining in foam
$\bar{X}$	3.24	3.23	8.34	3.96	.58	2.65	2.45
σ^2	0.0024	0.3819	0.1548	0.2332	0.0075	-	-

Table 9. SERIES 4 - USING FOAM SAMPLES ORIGINALLY DIPPED IN NO. 2 FUEL OIL (SERIES 2), NOW DIP IN WATER (8 SAMPLES USED)

	Foam weight in gms.	Weight of oil in gms. in foam before testing	Total weight of oil/water & foam in gms. after squeezing	Weight of oil in gms. squeezed from foam	Weight of water in gms. squeezed from foam	Weight of water in gms. remaining in foam	Weight of oil in gms. remaining in foam
$\bar{X}$	3.23	1.95	8.55	0.0	9.78	3.37	1.95
σ^2	0.0019	0.0125	0.065	0.0	1.417	-	-

SUMMARY OF TEST RESULTS (CONTINUED)

Table 10. SERIES 5 - WATER ABSORPTION TESTS WITH 20 ppi POLYURETHANE FOAM SAMPLES CUT INTO 4.44 cm x 4.44 cm x 1.9 cm STRIPS (5 SAMPLES USED).

	Foam weight in gms. before wetting	Foam weight in gms. after squeezing	Weight of water in gms. remaining in foam after squeezing	Weight of water in gms. squeezed from foam
$\bar{X}$	1.08	2.48	1.40	4.58
σ^2	0.0016	0.0256	-	-

Table 11. SERIES 6 - NO. 2 FUEL OIL ABSORPTION TESTS WITH 20 ppi POLYURETHANE FOAM SAMPLES CUT INTO 4.44 cm x 4.44 cm x 1.9 cm STRIPS (5 SAMPLES USED).

	Foam weight in gms. before wetting	Foam weight in gms. after squeezing	Weight of oil in gms. remaining in foam after squeezing	Weight of oil in gms. squeezed from foam
$\bar{X}$	1.10	2.16	1.06	1.44
σ^2	0.0	0.0024	-	-

Table 12. SERIES 7 - NO. 6 FUEL OIL ABSORPTION TESTS FOLLOWED BY WATER ABSORPTION TESTS WITH 20 ppi POLYURETHANE FOAM SAMPLES CUT INTO 7.62 cm x 7.62 cm x 1.9 cm STRIPS (3 SAMPLES USED).

	Foam weight in gms. before testing	Weight of foam sample in gms. after dipping & squeezing out oil	Weight of oil in gms. remaining in foam	Weight of foam in gms. after dipping in water & squeezing	Weight of water in gms. squeezed from foam	Weight of oil in gms. squeezed from foam	Weight of water in gms. remaining in foam
$\bar{X}$	3.3	13.7	10.4	14.9	10.5	0.0	1.2
σ^2	0.0	0.083	0.083	0.243	0.25	0.0	0.0

It can easily be seen that the individual water (Wo/Wi) and oil (Oo/Oi) ratios are respectively constant and are independent of the order in which the experiments were performed. Moreover, in comparing the results of test series 5 and 6 with those of 1 and 2, approximately the same ratios exist.

Series 1 - Wo/Wi = 10.92/3.69 = 2.96
Series 5 - Wo/Wi = 4.58/1.40 = 3.27

Series 2 - Oo/Oi = 4.25/2.66 = 1.60
Series 6 - Oo/Oi = 1.44/1.06 = 1.36

However, the actual quantities of oil and water remaining in the foam or squeezed from the foam are scaleable by the ratio of the surface areas of the different size foam strips. In this case that ratio is:

$$\frac{A_{surface\ (7.62\ cm)}}{A_{surface\ (4.44\ cm)}} = \frac{174.2}{73.2} = 2.38$$

Test series 7 is similar to test series 2 followed by 4 but with widely different oil viscosities. However, more test series 7 data are required in order to formulate the Oo/Oi and Wo/Wi ratios reported previously. Moreover, it appears that after the foam has been soaked and squeezed (independent of oil viscosity) no further oil can be obtained from the foam by the mechanical squeezing process used here. Further tests with the No. 6 fuel oil should be conducted in order to elucidate these points.

The results of these tests indicate that there exist certain fixed oil (Oo/Oi) and water (Wo/Wi) ratios. However, several important questions regarding the properties of polyurethane foam were not adequately addressed in the course of these experiments. Therefore, a second series of experiments were performed at a later date to answer more precisely the following questions: (1) does presoaking the polyurethane foam samples in either oil or water result in an increased oil retention capacity of the foam; (2) are the oil retention properties of the foam samples affected by multiple squeezings of these samples and (3) how do the oil retention characteristics of the foam samples vary with different types (i.e., ppi rating) of foam. A portion of question 1 was answered as a direct result of the comparison of the Oo/Oi ratios for test series 2, 3 and 6. These comparisons indicated that the Oo/Oi ratio remains essentially unchanged when the samples are presoaked in either oil or water; however, it does not adequately answer the question of what happens to the absolute values of the quantities Oo and Oi.

The second series of experiments were conducted under slightly different conditions than the first. The major changes in the experiment were as follows: (1) a different sample size of the polyurethane foam was employed since additional quantities of the previously used sample could not be found, and (2) two parallel steel rollers were used to squeeze the foam samples since it resulted in a higher and more uniform pressure applied to the fluid filled foam samples. The second series of laboratory experiments were performed as follows: two samples of each of three different types (10, 20 and 40 ppi) of polyurethane foam were cut to uniform size and weighed. The first sample of each type of foam was dipped into a beaker containing water for about 20 seconds. The sample was then weighed and squeezed; the resulting water was collected and weighed. The sample was then deposited into a beaker containing No. 2 fuel oil and the weighing and squeezing process repeated ten times. For comparison, the second sample of each type of foam was deposited in the No. 2 fuel oil only and the weighing and squeezing processes repeated ten times. The results of these tests are reported in Tables 13 through 18. The test parameters are as follows:

Fluid densities - water at 22°C = 1.0 gm/ml
No. 2 fuel oil at 22°C = 0.824 gm/ml

Foam dimensions - 10.50 cm x 10.50 cm x 2.55 cm sample
Volume = 281.1 cm^3
Surface area = 327.6 cm^2
Volume/surface area = 0.86 cm

The mean values as well as the individual test data for each foam type reported in Tables 13 through 18 indicate that for a particular foam type the absolute values of the quantities Oo and Oi are independent of whether or not the foam sample is initially dry or wetted with oil or water. This fact combined with the results from the previous test series concerning the constancy of the Oo/Oi ratio leads one to conclude that presoaking the polyurethane foam samples in either oil or water does not affect its oil retention capacity.

The data reported in Tables 13 through 18 does not show an increasing or decreasing trend over the ten tests. Instead, the data appears to oscillate around the mean values in a random manner. The 20 ppi data (Tables 15 and 16) appears to have a much larger error band than either the 10 or 40 ppi data. However, no particular reason for this error could be found after reviewing the experimental procedures used here.

Table 13. OIL ABSORPTION TESTS WITH 10 ppi POLYURETHANE FOAM SAMPLES CUT INTO 10.50 cm x 10.50 cm x 2.55 cm STRIPS (1 SAMPLE USED)

Test No.	Dry Wt. of foam in gms.	Wt. of Foam in gms.after wetting with No. 2 Oil	Wt. of Foam in gms.after squeezing out No. 2 Oil	Wt. of No. 2 oil squeezed from foam in gms.	Wt. of No. 2 oil remaining in foam in gms.
1	8.6	14.6	11.3	3.3	2.7
2	8.6	14.0	11.2	1.8	2.6
3	8.6	15.3	11.4	3.9	2.8
4	8.6	14.1	11.0	3.1	2.4
5	8.6	14.0	10.3	3.7	1.7
6	8.6	15.2	10.5	4.7	1.9
7	8.6	14.3	11.7	2.6	3.1
8	8.6	14.5	11.0	3.5	2.4
9	8.6	15.7	10.8	4.9	2.2
10	8.6	16.1	11.1	5.0	2.5
$\bar{X}$	8.6	14.78	11.03	3.65	2.43

Table 14. OIL/WATER ABSORPTION TESTS WITH 10 ppi POLYURETHANE FOAM SAMPLES CUT INTO 10.50 cm x 10.50 cm x 2.55 cm STRIPS (1 SAMPLE USED)

Test No.	Dry Wt. of foam in gm.	Wt. of foam in gms. after wetting with water	Wt. of foam in gms. after squeezing out water	Wt. of foam in gms. after wetting with No. 2 Oil	Wt. of foam in gms. after squeezing out No.2 Oil	Wt. of No. 2 oil squeezed from foam in gms.	Wt. of No. 2 oil remaining in foam in gms.
0	8.1	30.0	10.3	-	-	-	-
1	8.1	-	-	16.0	10.5	5.5	2.4
2	8.1	-	-	15.7	10.4	5.3	2.3
3	8.1	-	-	15.6	10.5	5.1	2.4
4	8.1	-	-	14.5	10.5	4.0	2.4
5	8.1	-	-	15.2	10.7	4.5	2.6
6	8.1	-	-	15.3	10.7	4.6	2.6
7	8.1	-	-	15.8	10.6	5.2	2.5
8	8.1	-	-	15.0	10.7	4.3	2.6
9	8.1	-	-	15.6	11.0	4.6	2.9
10	8.1	-	-	16.3	11.1	5.2	3.0
$\bar{X}$	8.1	30.0	10.3	15.50	10.67	4.83	2.57

Table 15. OIL ABSORPTION TESTS WITH 20 ppi POLYURETHANE FOAM SAMPLES CUT INTO 10.50 cm x 10.50 cm x 2.55 cm STRIPS (1 SAMPLE USED)

Test No.	Dry wt. of Foam in gms.	Wt. of Foam in gms. after wetting with No. 2 Oil	Wt. of Foam in gms. after squeezing out No. 2 Oil	Wt. of No. 2 Oil squeezed from foam in gms.	Wt. of No. 2 Oil Remaining in foam in gms.
1	7.6	28.6	9.5	19.1	1.9
2	7.6	26.0	9.6	16.4	2.0
3	7.6	27.2	9.3	17.9	1.7
4	7.6	28.3	9.6	18.7	2.0
5	7.6	28.4	9.6	18.8	2.0
6	7.6	26.1	9.4	16.7	1.8
7	7.6	26.7	8.9	17.8	1.3
8	7.6	26.7	8.8	17.9	1.2
9	7.6	25.4	8.9	16.5	1.3
10	7.6	28.1	9.0	19.1	1.4
$\bar{X}$	7.6	27.15	9.26	17.89	1.66

Table 16. OIL/WATER ABSORPTION TESTS WITH 20 ppi POLYURETHANE FOAM SAMPLES CUT INTO 10.50 cm x 10.50 cm x 2.55 cm STRIPS (1 SAMPLE USED)

Test No.	Dry Wt. of foam in gm.	Wt. of foam in gms. after wetting with water	Wt. of foam in gms. after squeezing out water	Wt. of foam in gms. after wetting with No. 2 Oil	Wt. of foam in gms. after squeezing out No.2 Oil	Wt. of No. 2 oil squeezed from foam in gms.	Wt. of No. 2 oil remaining in foam in gms.
0	7.6	35.0	9.2	-	-	-	-
1	7.6	-	-	28.5	9.4	19.1	1.8
2	7.6	-	-	26.3	9.2	17.0	1.6
3	7.6	-	-	25.3	9.1	16.2	1.5
4	7.6	-	-	26.5	9.2	17.3	1.6
5	7.6	-	-	26.6	9.1	17.5	1.5
6	7.6	-	-	24.7	9.2	15.5	1.6
7	7.6	-	-	27.7	9.0	18.7	1.4
8	7.6	-	-	25.2	8.4	16.8	0.8
9	7.6	-	-	27.2	9.0	18.2	1.4
10	7.6	-	-	25.0	8.9	16.1	1.3
$\bar{X}$	7.6	35.0	9.2	26.29	9.05	17.24	1.45

TABLE 17. OIL ABSORPTION TESTS WITH 40 ppi POLYURETHANE FOAM SAMPLES CUT INTO 10.50 cm x 10.50 cm x 2.55 cm STRIPS (1 SAMPLE USED)

Test No.	Dry wt. of Foam in gms.	Wt. of Foam in gms. after wetting with No. 2 Oil	Wt. of Foam in gms. after squeezing out No. 2 Oil	Wt. of No. 2 Oil squeezed from foam in gms.	Wt. of No.2 Oil Remaining in foam in gms.
1	7.8	45.0	10.4	34.6	2.6
2	7.8	47.9	10.7	37.2	2.9
3	7.8	47.2	10.6	36.6	2.8
4	7.8	47.4	11.0	36.4	3.2
5	7.8	48.3	10.8	37.5	3.0
6	7.8	49.4	11.1	38.3	3.3
7	7.8	48.6	11.0	37.6	3.2
8	7.8	52.4	11.1	41.3	3.3
9	7.8	50.0	10.6	39.4	2.8
10	7.8	51.4	11.2	40.2	3.4
$\bar{X}$	7.8	48.76	10.85	37.91	3.05

Table 18. OIL/WATER ABSORPTION TESTS WITH 40 ppi POLYURETHANE FOAM SAMPLES CUT INTO 10.50 cm x 10.50 cm x 2.55 cm STRIPS (1 SAMPLE USED)

Test No.	Dry Wt. of foam in gm.	Wt. of foam in gms. after wetting with water	Wt. of foam in gms. after squeezing out water	Wt. of foam in gms. after wetting with No. 2 Oil	Wt. of foam in gms. after squeezing out No.2 Oil	Wt. of No. 2 oil squeezed from foam in gms.	Wt. of No. 2 oil remaining in foam in gms.
0	7.9	75.5	10.3	-	-	-	-
1	7.9	-	-	47.0	11.2	35.8	3.3
2	7.9	-	-	49.0	11.1	37.9	3.2
3	7.9	-	-	45.7	11.4	34.3	3.5
4	7.9	-	-	50.0	11.4	38.6	3.5
5	7.9	-	-	46.8	11.5	35.3	3.6
6	7.9	-	-	44.4	11.4	33.0	3.5
7	7.9	-	-	47.0	11.5	35.5	3.6
8	7.9	-	-	46.1	11.5	34.6	3.6
9	7.9	-	-	48.8	11.4	37.4	3.5
10	7.9	-	-	47.9	11.4	36.5	3.5
$\bar{X}$	7.9	75.5	10.3	47.27	11.38	35.89	3.48

In answering the second question posed earlier, it can be seen that there is no effect of repeated squeezing of the foam on its oil retention characteristics. However, the number of tests (10) reported here are not sufficient to conclude that over a long period of time that this result will remain valid. Deterioration of the foam after many squeezings can occur and will eventually alter its oil retention properties. The data reported in Tables 13 through 18 clearly show that the oil retention capacity of the foam increases with its ppi rating, at least for the very light No. 2 fuel oil used here. The reason for this is that as the number of pores in the foam decrease, the oil flows through; whereas when the number of pores increase, the oil can be more easily contained within the foam. This situation may change for the very viscous oils because they tend to coat the surface of the larger ppi foams and are absorbed/adsorbed more readily by the low ppi foams. However, data for these more viscous oils were not obtained in this investigation.